Arnold Schwarzenegger
Governor

CLIMATE CHANGE AND WATER SUPPLY RELIABILITY

PIER FINAL PROJECT REPORT

DRAFT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
California Climate Change Center
University of California, Berkeley
Richard & Rhoda Goldman School of Public Policy

November 2004

Prepared By:
John A. Dracup, Sebastian Vicuna, Rebecca Leonardson
California Climate Change Center
University of California, Berkeley
Berkeley, CA
Contract No. 500-02-004
Work Authorization No. MR-006

Prepared For:
California Energy Commission
Public Interest Energy Research (PIER) Program

Guido Franco
Contract Manager

Kelly Birkinshaw,
Program Area Team Lead
Energy-Related Environmental Research

Ron Kukulka,
Acting Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert L. Therkelsen
Executive Director

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- FINAL REPORT –

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By:

John A. Dracup

Sebastian Vicuna

Rebecca Leonardson

California Climate Change Center
UC Berkeley
Richard & Rhoda Goldman School of Public Policy
Berkeley, CA 94720-7320
510-643-4578

Program Manager
Guido Franco
California Energy Commission

LEGAL NOTICE

ACKNOWLEDGEMENTS

We are grateful to Richard Palmer and Nathan VanRheenen of the University of Washington for generously lending us CVMod, and to Levi Brekke of the U.S. Bureau of Reclamation for helping us to understand and operate CALSIM-II. We also thank Larry Dale and Michael Hanemann for their advice and suggestions.

RECOMMENDED CITATION

John A. Dracup, Sebastian Vicuna, and Rebecca Leonardson. 2004. *Climate Change and Water Supply Reliability.* Califonia Climate Change Center California Energy Commission, PIER Energy-Related Environmental Research. Contract No. 500-02-004.

TABLE OF CONTENTS

PREFACE . . . . **v**
ABSTRACT 1
EXECUTIVE SUMMARY 2
REPORT ORGANIZATION . . . . ?

I. ***Introduction*** . . . . ?

2. ***Review of Climate Change Literature in California*** . . . . ?
2.1 Lund et al (2003), UC Davis . . . . ?
2.2 VanRheenan et al (2004), University of Washington . . . . ?
2.3 Brekke et al (2004), UC Berkeley - LBL . . . . . . ?
2.4 Yao and Georgakakos (2001) . . . . ?
References . . . . ?

3**A.** ***Choosing a Water Resources Model for Climate Change Studies in California***. ?
3.1 Introduction . . . . ?
3.2 Comparison of water resources models available for California: CALSIM, CALVIN and CVMod . . . . ?
3.3 Results derived from the use of these models . . . . . ?
3.3.1 Assessing California water system reliability using CALSIM-II model ?
References . . . . ?
Appendix 3A.1 . . . . ?
Appendix 3A.2 . . . . ?
3A.2.a. CALSIM-II . . . . ?
3A.2.b CALVIN . . . . ?
3A.2.c CVMod. . . . . ?
Appendix 3A.3 Comparison of CVMod and CALSIM results with historic DWR data ?
Appendix D.4 Assessing California water system reliability using CALSIM-II model ?

3B ***Accuracy of DWR Water Flow Forecasts*** . . . . . . ?

List of Figures . . . . ?
Figure 2-1: Predicted 2000-2098 mean monthly regulated Delta inflows and Sacramento and San Joaquin total storages given current operating rules and year 2001 demands and hydrologic development . . . . . . ?
Figure 2-2: Simulated Surface Water Supplies for the Combine Sacramento and San Joaquin River Regions, and for the San Joaquin region only. . . . ?
Figure 3A-1: Geographic location of users within CALSIM-II. . . . . ?
Figure 3A-2: Schematic showing group of users within CALSIM-II. . . ?
Figure 3A-3: Annual reliability for all users in the Central Valley . . . ?
Figure 3A-4: Monthly reliability for all users in the Central Valley . . . ?

Figure 3A-5: Annual reliability for broad categories of user in the Central Valley . ?
Figure 3A-6: Monthly reliability for broad categories of users in the Central Valley ?
Figure 3A-7: Annual reliability for non-project users north of the Delta . . ?
Figure 3A-8: Monthly reliability for non-project users north of the Delta . . ?
Figure 3A-9: Annual reliability for SWP contractors South of Delta. . . ?
Figure 3A-10: Monthly reliability for SWP contractors South of Delta . . ?
Figure 3A-11: Annual reliability for CVP contractors South of Delta . . ?
Figure 3A-12: Monthly reliability for CVP contractors South of Delta . . ?
Figure 3A-13: Annual reliability for different East San Joaquin streams' users . ?
Figure 3A-14: Monthly reliability for different East San Joaquin streams' users . ?
Figure 3A-15: DSAs represented in CALSIM-II (enclosed by polygons) . . ?
Figure A-3A-1: Comparison of end of month Shasta storage levels . . . ?
Figure A-3A-2: CALSIM-II and CVMod standardized deficit/surplus in Shasta storage level compared to historic data . . . . . . ?
Figure A-3A-3: Comparison of end of month Trinity storage levels . . . ?
Figure A-3A-4: CALSIM-II and CVMod standardized deficit/surplus in Trinity storage level compared to historic data . . . . . . ?
Figure A-3A-5: Comparison of end of month Whiskeytown storage levels . . ?
Figure A-3A-6: CALSIM-II and CVMod standardized deficit/surplus in Whiskeytown storage level compared to historic data . . . . . ?
Figure A-3A-7: Comparison of end of month Oroville storage levels . . ?
Figure A-3A-8: CALSIM-II and CVMod standardized deficit/surplus in Oroville storage level compared to historic data . . . . . . ?
Figure A-3A-9: Comparison of end of month Folsom storage levels. . . ?
Figure A-3A-10: CALSIM-II and CVMod standardized deficit/surplus in Folsom storage level compared to historic data . . . . . . ?
Figure A-3A-11: Comparison of end of month San Luis CVP storage levels . ?
Figure A-3A-12: CALSIM-II and CVMod standardized deficit/surplus in San Luis CVP storage level compared to historic data . . . . . ?
Figure A-3A-13: Comparison of end of month San Luis SWP storage levels . ?
Figure A-3A-14: CALSIM-II and CVMod standardized deficit/surplus in San Luis SWP storage level compared to historic data . . . . . ?
Figure A-3A-15: Comparison of end of month Camanche + Pardee storage levels . ?
Figure A-3A-16: CALSIM-II and CVMod standardized deficit/surplus in Camanche + Pardee storage level compared to historic data . . . . ?
Figure A-3A-17: Comparison of end of month New Hogan storage level . . ?
Figure A-3A-18: CALSIM-II and CVMod standardized deficit/surplus in New Hogan storage level compared to historic data . . . . . ?
Figure A-3A-19: Comparison of end of month New Melones storage level . . ?
Figure A-3A-20: CALSIM-II and CVMod standardized deficit/surplus in New Melones storage level compared to historic data . . . . . ?
Figure A-3A-21: Comparison of end of month New Don Pedro + Lake McClure storage levels . . . . ?

Figure A-3A-22: CALSIM-II and CVMod standardized deficit/surplus in New Don Pedro + Lake McClure storage levels . . . . ?
Figure D.4-1: Geographic location of users within CALSIM-II . . . ?
Figure D.4-2: Schematic showing group of users within CALSIM-II . . ?
Figure 3B-1: Mokelumne River Forecast Analysis . . . . . . ?
Figure 3B-2: Feather River Flow Forecast Analysis . . . . . ?
Figure 3B-3: Yuba River Flow Forecast Analysis . . . . . . ?
Figure 3B-4: American River Flow Forecast Analysis . . . . ?
Figure 3B-5: San Joaquin River Flow Forecast Analysis . . . . ?
Figure 3B-6: Kings River Flow Forecast Analysis . . . . . . ?
Figure 3B-7: Dry Years Flow Forecast Analysis . . . . . ?
Figure 3B-8: Wet Years Flow Forecast Analysis . . . . . . ?

List of Tables . . . . ?

Table 2-1: Summary of some recent works on climate change impacts in California ?
Table 2-2: Statewide scarcity costs for different climate change scenarios ($ million/yr) . . . . ?
Table 2-3: Folsom Lake operations' assessments for future climate scenarios . ?
Table 3A-1: Comparison between three water resources models for California . ?
Table 3A-2: Strengths and limitations of CALSIM-II and CVMod . . . ?
Table 3A-3: Overall reliability measure of water supply deliveries for different water users in California . . . . ?
Table A-3A-1: Some differences between Simulation and Optimization models . ?
Table A-3A-2: Comparison between CVMod and CALSIM results and DWR historic data on reservoirs storage in the Central Valley . . . . ?
Table D.4-1: CALSIM-II variables representing the demands and deliveries for different water users in the Central Valley, used to estimate the reliability measures. ?

PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering up with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-use Energy Efficiency
- Renewable Energy Technologies

What follows is a report on work conducted under Contract #500-02-006, Preliminary Economic Analyses of Climate Change Impacts and Adaptation and GHG Mitigation, Work Authorization MR-006 by the California Climate Change Center at UC Berkeley. This report is entitled *Climate Change and Water Supply Reliability*. This project contributes to the PIER Energy-Related Environmental Research Program.

ABSTRACT

We are conducting a broad spectrum of studies of the California water system to assess the impacts of climate change on urban and agricultural water agencies. These topics include methods for measuring water supply reliability, methods for projecting changes in supply reliability, caused by climate change. This report describes preliminary work on these topics including: (1) a review of the recent climate change literature in California; (2) a summary of criteria for evaluating different water resource models described in that literature and (3) an assessment of CALSIM-II water supply reliability forecasts.

Part one of the report includes reviews of studies by Lund et al (2003), Van Rheenan et al (2004), Brekke et al (2004) and Yao and Georgakakos (2001). These studies show that climate change will impact Californian hydrology in several ways, including an earlier start of spring snowmelt, an increase in winter runoff as a fraction of total runoff, and an increase in winter floods frequency. The ultimate impact on California water resources, power generation and flooding will depend on the ability of the man-made infrastructure to cope with these changes.

Part two of the report evaluates three models used to estimate the water supply impacts of changing climate scenarios. These models include: (1) CALSIM-II developed jointly by DWR and U.S. Bureau of Reclamation; (2) CALVIN developed at U.C. Davis; and (3) CVMod developed at the University of Washington. Performance criteria are used to evaluate these models, including descriptive accuracy, hydrologic flexibility, spatial resolution and ex-anti forecast accuracy. This comparison reveals the different strengths and weaknesses of the models, following these performance criteria.

CALSIM-II benchmark studies reveal differences in water supply reliability to user groups in part three of the report. The studies show that supply reliability at the aggregate basin level differs markedly from reliability at the DSA and other sub groups within basins. Another conclusion is that the distribution of reliability in annual terms is different than the distribution of reliability in monthly terms.

EXECUTIVE SUMMARY

Climate change in California is a source of growing concern; the various impacts it will have on the state's agricultural industry could be potentially damaging. Major economic impacts are likely to be manifested through the state's water system. In this project, our objective is to assess the economic costs associated with potential changes in the reliability of supply for water users in various parts of the state. Previous research on water use in California has generally used data gathered from broad geographic aggregates. Our research differs in that we gather and analyze data from individual water districts; this is necessary because there is considerable heterogeneity among different water districts in California with regard to the source of water, the nature and age of water rights, the cost of operations, finances, price structures, and other terms of service. Also, unlike previous studies, we focus specifically on measuring water supply reliability and the uncertainty that confronts water users at the time of the year when they need to make major decisions about water use. This approach is used here because climate change in California is likely to affect users primarily through its impact on supply reliability and uncertainty.

Important decisions about water use, such as crop choice or predicting the degree of a water shortage, are made at the beginning of the high usage period by both farmers and urban water managers, typically around April, creating an inherent uncertainty in the decision process. Much of the water use that occurs in California between April and September is likely to be determined by expectations about the amount of water that will be available during the coming summer. Most of the existing hydrologic/economic models represent water supply through actual, historical monthly deliveries, which represents the ex post outcome and obscures -- and, ultimately, ignores – the underlying ex ante uncertainty. The timing of water use decisions by most agricultural and urban water agencies in California is such that the ex ante probability of obtaining water during the warm season has the most impact on these decisions.

To assess the impacts that climate change in California is likely to produce, with regard to the existing mismatch between both where and when rains falls and where and when people need to use water, we are conducting a broad spectrum of studies on the California water system, including six main components: (1) determining the existing reliability (degree of certainty) of the water supply for various irrigation districts and urban water agencies around the state; (2) conducting an econometric analysis, which will measure the economic consequences of differences in supply reliability and ultimately will be used to develop economic loss functions for changes in agricultural water supply reliability due to climate change; (3) conducting an econometric analysis based on cross-section and time-series data on urban water use for urban water agencies in California to estimate demand functions for water, which will determine the demand elasticities that we will use to project future urban water demand in areas of new urban growth in California; (4) projecting future agricultural and urban water demand and supply in California in the absence of climate change; (5) assessing how climate variability and change will impact the reliability of water supply for urban and agricultural water agencies in California by evaluating alternative models to estimate the impact of climate change on water supply; and (6) assessing the economic consequences of the future changes in supply reliability for urban and agricultural water users in California due to climate change. The research reported here focuses on the first and fifth of these components.

The existing literature suggests that global warming is likely to have significant impacts on the hydrological cycle which in turn will affect many aspects of the California water system. There is evidence that some changes have already occurred, such as an earlier start of the spring snowmelt, an increase in winter runoff as a fraction of total runoff, an increase in winter floods frequency, changes in total runoff that depend on the model implemented and a more significant impact from global warming on river basins located in medium altitudes. Other studies have suggested that shifts in runoff without accompanying operational changes will challenge the systems and perhaps reduce the reliability with which the systems meet current demands. Ultimately, the impact on California water resources will depend on the ability of human management system and infrastructure to cope with these changes.

In order to effectively assess these impacts, a water resources model is needed that represents the operation of the California water system. This model will use the new runoffs derived from climate change impact studies of the Central Valley hydrology to estimate water supplies throughout the systems. The model needs to adopt a descriptive rather than prescriptive approach, it needs to provide hydrologic flexibility, and it should offer a good representation of the system in terms of comprehensiveness of overage, spatial resolution, and validity in the characterization of operation policies and constraints. To date, we have analyzed three models: CALVIN, CALSIM-II and CVMod. In addition, we have studied the Riverware modeling system developed at the University of Colorado. At this point, none of these models fully meets these criteria for adequacy. The CALVIN model is prescriptive, rather than descriptive. CALSIM-II is a descriptive model with good representation of the system in terms of coverage, spatial resolution and current operation rules. But its major fault is its inability to be run using a sequence of hydrologic inputs not strictly related to the 73 years of historic hydrologic inputs to which the model is bounded; also it is non-uniform in terms of how water deliveries are set for different geographic areas. CVMod is also a good descriptive model with the ability to be run by any hydrologic inputs but CVMod's weakness is that some of the operation rules and, hence the results of using this mode, could be far from how the system is actually being run. At this point, there is no single model fully suitable for our purposes.

Using the most recent results from CALSIM-II, the Benchmark simulation runs, we find that: 1) water supply reliability is not the same among different water users in the Central Valley; 2) the distribution of reliability in annual terms is different than the distribution of reliability in monthly terms but they are quite similar when the overall measure of reliability is compared; deficits in supply are concentrated in only *certain months* in the year; 3) different project contractors have different reliabilities according to their water right status; 4) the annual reliability curve for non-project users show that water supplies are mostly constant throughout the 73 years of different hydrologic conditions; 5) and there are large differences in terms of reliability for different East San Joaquin users

The final section in this report is related to measurement of the ex ante uncertainty in water deliveries. The goal of this research on the accuracy of DWR water delivery forecasts is to measure the error bands that might be placed around these forecasts. The forecasts of water deliveries and streamflows, published by the DWR at the beginning of each year, are likely to be a crucial input to water district managers' expectations regarding their warm-season water supplies, yet since these are only forecasts, they are likely to contain some degree of error. In our research, we have determined that forecast accuracy not only improves over time as the period between the forecast date and delivery shortens, but it also seems to improve with watershed elevation; higher watersheds tend to have more accurate forecasts than lower watersheds. This correlation may be related to the dominance of snowmelt in the annual hydrograph of higher watersheds. If so, reduction of the snowpack due to climate change can have a substantial impact on future forecast reliability.

For future research, we have designated some areas of interest, including the accuracy of forecasts for higher elevation watersheds, the difference in the range of forecasts between higher elevation watersheds and lower elevation watersheds, the faster and more uniform convergence of forecasts for higher elevation watersheds as compared to those for lower elevation watersheds, and the discrepancy in the 50% exceedance forecasts, which shows that these forecasts tend to slightly underestimate actual deliveries for higher elevation watersheds and overestimate deliveries for lower elevation watersheds.

I. Introduction

The major pathway by which climate change will affect the California economy is through its impact on the California water system. Therefore, an economic analysis of the California water system to assess the economic costs associated with changes in the reliability of supply for water users in various parts of the state forms a major component of the research being conducted at Berkeley.

Compared to previous research, the approach we have adopted for measuring the economic impacts of climate change has two distinctive features.

First, our primary spatial unit of analysis is the service areas of individual retail water supply agencies – irrigation districts and urban water agencies – as opposed to broader geographic aggregates of districts such as depletion analysis areas. To the maximum extent possible, our analysis will be disaggregated to the level of the individual water district. The reason why we wish to avoid any further aggregation is that there is tremendous heterogeneity among different water districts even within the same county in California with respect to their source of water, the nature and age of their water rights, their cost of operation, their finances, the price they charge their retail customers and other aspects of their terms of service; because of this diversity, aggregation is likely to be misleading and to introduce error into the analysis.

Second, unlike previous studies, we are focusing explicitly on supply *reliability* and the *uncertainty* over supply that confronts water users around the state at the time when they make their important decisions regarding water use. We seek to measure this explicitly, both in the baseline situation and in climate change scenarios. We are doing this because we believe that climate change in California is likely to affect water users primarily through its impact on supply reliability and uncertainty. This has not been analyzed in the existing work on climate change in California.

In this context, it is important to note the uneven temporal distribution of water supply and water use in California: roughly 80% of the state's precipitation falls between October and March, but about three quarters of all the water use in California occurs in the spring and summer, between April and September. What happens – or does not happen -- during that period is the key to whether the state's economy is benefited or harmed by water supply that year. Moreover, many important decisions that determine water use during this period are made *at the beginning* of the period. Farmers decide which crops to plant (and whether or not to replace perennials) in the early spring, around March or early April. Once they have made that decision, they are limited in the degree to which they can vary their use of water during the growing season -- they can under-water their crops, or even abandon them, if it subsequently happens that they receive less water than they had anticipated at the time of planting, but they cannot switch to a different crop nor is it practical for them to make major change in irrigation technology during the growing season. With urban water use the context is somewhat different, but there is still a critical window for decision around April in that, if urban water managers think there is a fair chance that they will experience some degree of water shortage during the coming warm season, they generally need to put out a call for voluntary (or mandatory) conservation no later than the end of spring. This sets up a pattern of water demand in their service area over the summer that is likely to be, at best, only partially reversible if water supplies turn out to be more abundant than originally anticipated. For somewhat similar reasons, environmental water managers in California, too, face a key decision point around April: because of the time lags in securing water supplies and arranging for their transfer, if managers are to meet critical in-stream needs during the warm season they will need to take action by the end of spring. For these reasons, much of the water use that occurs in California between April and September is likely to be determined by water agencies' *expectations*, as of the beginning of this period, regarding the amount of water that will become available to them during the coming summer. Supply reliability needs to be assessed by reference to these expectations.

Most of the existing hydrologic/economic models – both in California and elsewhere – deal with supply uncertainty by ignoring it. They represent water supply using the actual, historical monthly deliveries. This amounts to characterizing uncertainty by the *ex post* realization of the random variable, which effectively eliminates the uncertainty. However, as explained above, given the timing of water use decisions in California it is clearly the *ex ante* probability of obtaining water during the warm season (late spring and summer), as assessed some time around March or April, that has the most powerful influence on water users' decisions in California. Furthermore, it is reasonable to expect that these decisions will typically exhibit a significant degree of *risk aversion*. The important implication is that water use decisions are likely to depend not just on the mean of the ex ante probability distribution of warm-season water supply but also on other parameters of the distribution such as the semi-variance or the tail probabilities. In order to develop a linkage between changes in supply reliability and consequent economic impacts, one has to characterize supply reliability in terms of relevant parameters of the ex ante probability distribution of warm-season water supply. Given the observations above about the heterogeneity among water districts with regard to their water supply, these distributions generally need to be assessed for each district separately.

Implementing our approach, with its novel focus on measuring supply reliability at the level of individual water districts, is a major challenge because of the limitations in the data that are readily available in California. It is easy to obtain data on historical water deliveries for the two big projects (CVP, SWP) and for groups of irrigation districts combined into depletion study areas (DSAs). Obtaining historical flow data for individual districts not served by the two projects is often difficult. An obtaining a representation of the likely expectations of district managers in the form of an ex ante probability distribution is a major research task that has not previously been undertaken in California.

To deal with problems caused by the limited availability of data, we are pursuing a flexible and iterative strategy. Under this strategy, we are iterating between data collection and data analysis. In our first year of research, we started by collecting the most readily available data and then pushed on to conduct a preliminary analysis of these data recognizing that, while the data are still incomplete, many methodological issues arise during the course of data analysis and it is useful to start confronting them as early in the research as possible. While conducting the preliminary data analysis, we continue to work to expand the data and fill in the gaps. After a second round of data collection efforts, we will take a second crack at the data analysis, while still continuing with efforts to complete the data collection and with a view to a subsequent final data analysis. Thus, rather than working in sequence, we are conducting the various components of our analysis in parallel.

In California, climate change is likely to severely exacerbate the existing mismatch between where and when rain falls and where and when people need to use water. To assess these impacts we are conducting a broad suite of studies on various aspects on the California water system. The overall research involves six main components:

(1) Measure the existing reliability (degree of certainty) of the water supply for various irrigation districts and urban water agencies around the state given their various sources of supply, and their water rights or water contract entitlements. To accomplish this task we identify specific water users (agricultural, urban) who will be the focus of the study, and assemble a database of information on their water supply (contractual water entitlements, water rights, other sources of supply, within-district storage, etc); their water demand (cropping pattern, population, number of industrial, commercial and residential customers etc); and the economic value of water to their customers (e.g. water costs and pricing, crop prices, other input prices, farmland values, etc).

(2) Conduct an econometric analysis based on cross-section and time-series data of the relationships between supply reliability and economic outcomes for irrigation districts in California, including agricultural practices, choice of crops, farm profit and land values. These relationships measure the economic consequences of differences in supply reliability, and will be used to develop economic loss functions for changes in agricultural water supply reliability.

(3) Conduct an econometric analysis based on cross-section and time series data on urban water use for urban water agencies in California to estimate demand functions for water. The resulting short- and long-run price elasticities of demand will be used to develop short- and long-run loss functions for shortages in urban water supply in

California. The demand elasticities with respect to conservation variables will be used to assess the future potential for reducing urban demand via conservation. And, the demand elasticities with respect to climate variables, housing density, and housing vintage will b e used to project future urban water demand in areas of new urban growth in California.

(4) Project future agricultural and urban water demand and supply in California in the absence of climate change, based on economic and demographic scenarios, and projections of land use conversion and patterns of future urban growth in California. This analysis will incorporate results from the econometric analyses conducted in (2) and (3).

(5) Assess how climate variability and change will impact the reliability of water supply – the ex ante probability distributions – for urban and agricultural water agencies in California. In this task, we evaluate alternative models to estimate the impact of climate change on water supply and the factors that determine runoff forecasting and how they relate to climate inputs (e.g. how does the amount of water stored in the snowpack affects the accuracy in forecasting).

(6) Assess the economic consequences of the future changes in supply reliability for urban and agricultural water users in California identified in (5) when applied to the future scenarios developed in (4), using the economic loss functions developed in (2) and (3).

The research conducted during our first year has focused on (1), (2) and (3). In addition, we have started to employ the results of the recent paper in the Proceedings of the National Academy of Sciences dealing with the effects of climate change on California hydrology as a preliminary practice for doing (5). We are also getting prepared to perform tasks (4) and (5), specifically looking at the different water resources models available for California that would be needed to assess future hydrologic conditions.

The research described here has two components: the first is an overview of the ongoing process to choose the most appropriate water resources model to be used in tasks (4) and (5) as just described and an assessment of historic water supply reliability in California performed using CALSIM-II. We have also included a short review of California's water resources climate change related literature.

II. Review of Climate Change Literature in California

The latest 2001 Intergovernmental Panel on Climate Change (IPCC) report reaffirms that climate is changing in ways that cannot be accounted for by natural variability and that “global warming” is occurring (IPCC, 2001). The IPCC reports that climate model projections with a transient 1% annual increase in greenhouse gas emissions show an increase in the global mean near-surface air temperature. The temperature increase ranges from 1.4°C to 5.8°C, with a 90% probability interval of 1.5°C to 4.5°C by 2100 (Wigley and Raper, 2001).

This global warming is likely to have significant impacts on the hydrological cycle affecting many water resources systems (IPCC, 2001; Arnell, 1999). Californian water resources are also expected to suffer from the effects of global warming. Moreover, there is evidence that some change has already occurred: increasing temperatures have changed the runoff pattern of several watersheds of the Sierra Nevada. The trend is to have more runoff in the winter season and less in the spring-summer season (Dettinger and Cayan, 1995). There have been a number of investigations of California hydrologic response focused on changes in streamflow due to climate change as Miller et al. (2003) pointed out in a summary of the first works in this subject. Again, as the historic record already indicates, these studies have suggested that Sierra Nevada snowmelt driven streamflows are likely to peak earlier in the season under global warming due to increased atmospheric greenhouse gas (GHG) concentrations.

The most recent work studying the effects of climate change in Californian hydrology was done by groups at the Lawrence Berkeley National Laboratories, LBL (Miller et al (2003)), the Scripps Institution of Oceanography (Stewart et al, 2004; Dettinger et al, 2004) and the University of Washington (Vanrheenen et al, 2004). Although, these studies used different Global Circulation Models (GCM) different methodologies for downscaling the GCM results to derive the regional hydrologic changes (see Table 2-1), their results show consistently that climate change will impact Californian hydrology by:

- An earlier start of spring snowmelt.
- An increase in winter runoff as a fraction of total runoff.
- An increase in winter floods frequency
- Changes in total runoff amount that depend on the GCM used. There are the two GCMs used in these studies, the PCM and HadCM2. The former show results that are cooler and drier than the latter.
- The results vary by basin, with the key parameter being the basin elevation relative to the freezing line location during snow accumulation and melt periods. Basins located at medium altitudes will be more affected by climate change.

Table 2-1. Summary of some recent works on climate change impacts on California hydrology

	LBL (1)	*SCRIPPS-USGS (2)*	*U. of Washington (3)*
GCM used and GHG emission scenario	Two GCMs: A warm wet HadCM2 (run 1) and a cool dry PCM (run B06.06).	PCM with a business as usual (BAU) emission scenario (run B06.44) plus some control runs.	PCM with: 3 BAU scenarios with different initializations; a control (CO2 at 1995 level); and an historic (CO2 at pre-industrial level) run.
Downscaling method	Statistical downscaling plus Sacramento and Anderson Snow hydrological models for 6 basins distributed along the Sierra Nevada: Feather, Kings, American, Merced, Sacramento, Smith.	Two methods: A statistical downscaling plus a Precipitation–Runoff Modeling System for three basins: Merced, American and Carson; and a regression analysis for snowmelt timing and Temperature and Precipitation Index (TI and PI).	Statistical downscaling plus Variable Infiltration Capacity (VIC) model to a set of basins in the Sacramento River System and the San Joaquin River system.

Sources:

(1) Miller et al. (2003)

(2) Dettinger et al, (2004); Stewart et al, (2004)

(3) Vanrheenan et al, (2004)

Most of the streamflows in the Sierra Nevada are regulated by large reservoirs. Changes in the streamflows that feed these reservoirs will change their ability to serve all the functions for which they are designed: flood control, water supply, hydropower generation, navagation and recreation. Reservoirs provide flood control during the winter wet season, when they need to have flood space requirements. This flood control space requirement limits the amount of water stored during the wet season. However, a substantial amount of winter precipitation is stored in the snowpack in the Sierra Nevada and during the spring (late March, April, and May), when flood control requirements are eased the reservoirs fill from spring snowmelt. Reservoirs are operated through the year using rule curves that represent the desired storage levels according to these flood-space filling requirements. These rule curves have been derived from historic hydrologic conditions and hence will not be reliable in the event of a change from the historic hydrology. This hydrology expected as a result of climate change implies an earlier and smaller spring runoff. This would make it more difficult to refill reservoir flood space during the late spring and early summer, thus reducing the amount of water supply that can be delivered (Roos, 2003).

The ultimate impact on California water resources will depend on the ability of the man-made infrastructure to cope with these changes. The performance of the California water system under climate change scenarios was first studied by Lettenmaier and Sheer (1991), and separately by Sandberg and Manza (1991) who examined the implications of climate changer scenarios for the performance of the State Water Project and the Central Valley Project. According to a review by Gleick and Chalecki (1999), "both studies concluded that the shifts in runoff without accompanying operational changes will challenge the systems and perhaps reduce the reliability with which the systems could meet current demands." More recently there have been four studies of the impacts of climate change on California water resources. The following is brief description of these works.

Lund et al (2003), UC Davis

The first of these studies was performed by Lund et al. (2003) at UC Davis as part of the PIER Research Program of the California Energy Commission (CEC). Lund et al (2003) used the results of the hydrologic modeling performed by Miller et al (2001) as inputs for the CALVIN statewide water resources optimization model[1], assuming that (1) all changes in dry season inflows directly affect water deliveries (because water is most easily managed during the dry season); (2) increases in wet season surface inflows are lost because of low water demand and low surface storage flexibility resulting from flood control;[2] and (3) no new infrastructure is constructed. Lund et al. (2003) estimated the economic impacts of climate change for two GCM results: HadCM and PCM. These impacts are expressed in terms of the outage (scarcity) costs under the assumption of optimal allocation of water among regions and user types in the year 2100, using an estimate of the statewide population expected at that time. The results, summarized in Table 2-2, show that the impact of climate change on urban users is comparatively small, while that on agricultural users is much larger. This comes about as a result of extensive water transfers which are assumed to occur on a month-by-month basis with perfect foresight, and no institutional constraints (such as water rights limitations). Population growth is projected to have a much greater effect on urban water use than does climate change because the model assumes that urban areas can purchase much of the water they need from agricultural areas under unfavorable climates. However, the effect of climate change on agriculture water deliveries is greater than the effect of population growth, especially for the dry climate change scenario (i.e. PCM) (Lund, et al 2003).

[1] See Section V below for a description of CALVIN and other water resources models for California.

[2] Water available throughout the region was obtained extrapolating the results for the 6 basins considered in Miller et al.(2001) using a mapping methodology from these basins to each of the 37 rim flows considered in the CALVIN model and taking into account the constraints in reservoir operations just described. Groundwater supplies were also considered. The CALVIN model is an economic-engineering driven optimization model developed at the University of California, Davis that has 37 inflows into the Central Valley from the surrounding mountains, which are called rim inflows. Historically, these rim inflows average 28.2 maf/yr, accounting for 72% of all inflows into CALVIN's California intertied water system (Lund et al., 2003).

Table 2-2. Statewide scarcity costs for different climate change scenarios ($ million/yr)

Cost	SWM2100[1]	PCM2100[2]	HadCM2100[3]
Urban Scarcity Costs	785	872	782
Agric. Scarcity Costs	198	1,774	180
Total Scarcity Costs	983	2,646	962

Notes

[1] Optimized model for year 2100 without changes in water availability. Scarcity costs accounts for increasing demand mainly.

[2] Optimized model for year 2100 with water deliveries decreases according to results of PCM scenarios

[3] Optimized model for year 2100 with water deliveries decreases according to results of HadCM2 scenarios

Source: Lund et al., 2003

VanRheenen et al (2004), U of Washington

Vanrheenen et al. (2004) also analyzed the impacts of climate change on Californian water resources. This group used their own runoff estimates (see Table 2-1 for a description of their work in that regards) as inputs for CVMod, a monthly time step water resources simulation model that incorporates the major projects and operational features of the Sacramento-San Joaquin basin. CVMod was used to explore system performance and reliability given various operating policies and alternative climate and operating scenarios. Under the climate change scenario, CVMod results (see Figure 2-1) showed a decrease in inflows North and South of the Delta as well as a decrease in storage levels in reservoirs in both regions. These decreases in available water affected hydropower production and the reliability of fish and other environmental targets. A series of mitigation strategies (e.g. changes in the rule curves of reservoir releases) were considered, but even with the most comprehensive one “achieving and maintaining status quo (control scenario climate) system performance in the future would be nearly impossible, given the altered climate (change) scenario hydrologies”.

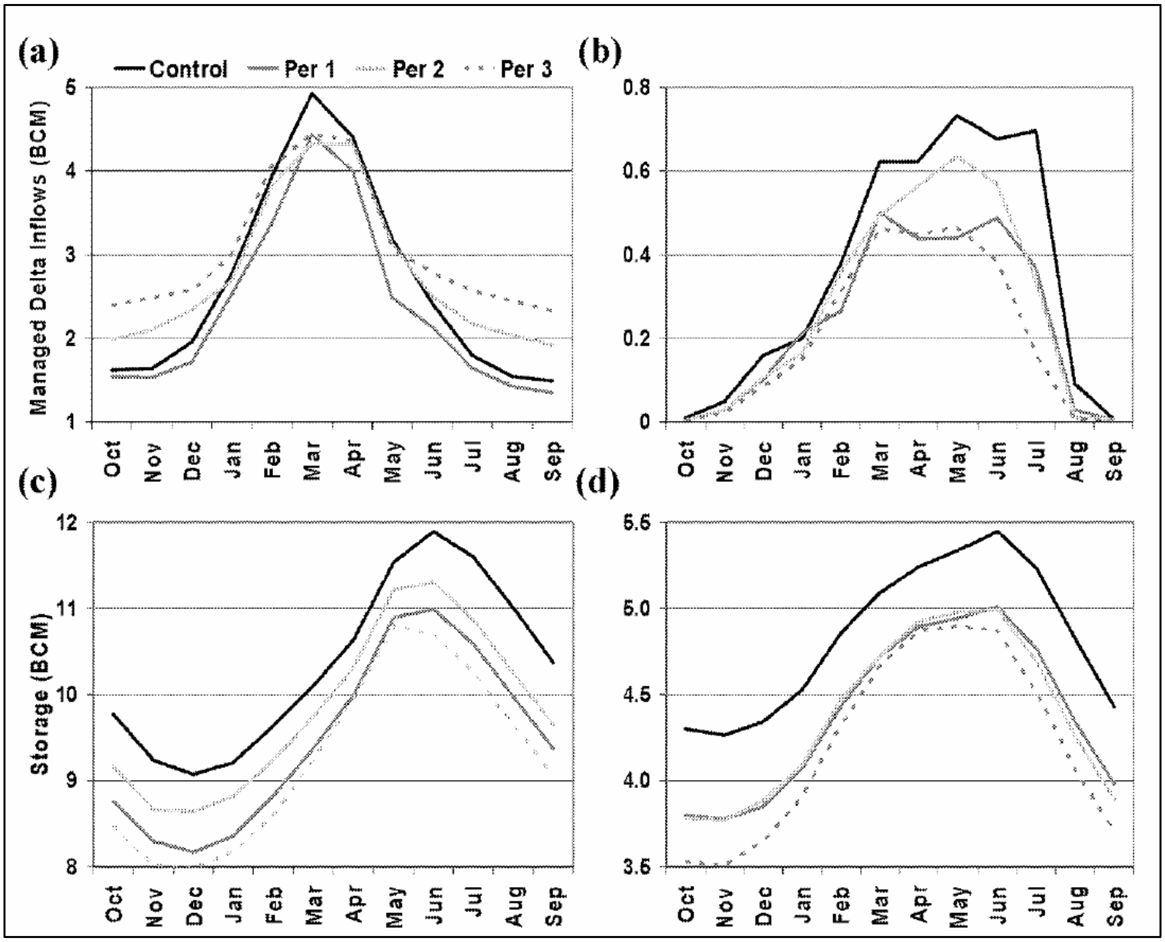

Figure 2-1. Predicted 2000–2098 mean monthly regulated Delta inflows and Sacramento and San Joaquin total storages given current operating rules and year 2001 demands and hydrologic development.

Notes: (a) Regulated flows at the mouth of the Sacramento River and (b) at the mouth of the San Joaquin River; (c) total reservoir storage north of the Delta (i.e., Sacramento River System) and (d) south of the Delta (i.e., San Joaquin River System). The future scenario results (for the period 2000–2098) are partitioned into three 30-year periods, termed Periods 1, 2, and 3, respectively: 2010–2039, 2040–2069, 2070–2098. Source: Vanrheenen et al (2004).

Brekke et al (2004), UC Berkeley-LBL

Finally, another study was performed by researchers at UC Berkeley and the Lawrence Berkeley National Laboratories (Brekke *et al.,* 2004). In this work, Brekke et al.(2004), using the runoff results derived by Miller et al (2001) for two global projections of GHG increase (PCM and HadCM2), derived mean monthly streamflow changes that were mapped onto 72 years of monthly historical streamflow for the reservoir inflows in the San Joaquin River region of California. Impacts downstream of the reservoirs were simulated using the California Water System Simulation Model (CALSIM) II 2001 Benchmark Study, which was developed by the California Department of Water

Resources in collaboration with the U.S. Bureau of Reclamation Mid-Pacific Region office. The results (shown in Figure 2-2) show a great dependence on the GCM used to derive runoffs. HadCM2 projects faster warming than PCM. HadCM2 and PCM project wetter and drier conditions, respectively, relative to present climate. In the HadCM2 case, there would be increased reservoir inflows, increased storage limited by existing capacity, and increased releases for deliveries and river flows. In the PCM case, there would be decreased reservoir inflows, decreased storage and releases, and decreased deliveries. The divergence in the results (both equiprobable), are attributable to the divergence in the precipitation projections of the GCM models as was mentioned before.

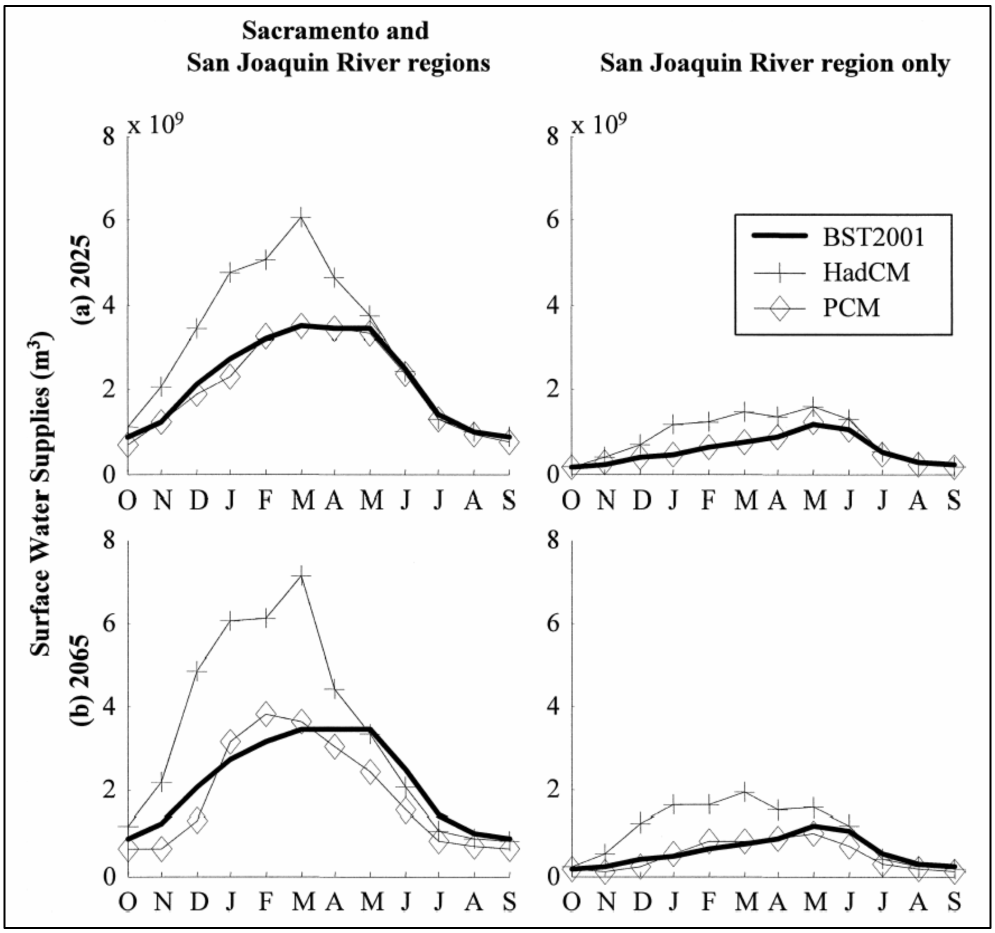

Figure 2-2. Simulated Surface Water Supplies for the Combine Sacramento and San Joaquin River Regions, and for the San Joaquin region only: (a) 2025 and (b) 2065.

Notes: BST stands for current climate CALSIM-II 2001 Benchmark Studies

Yao H, and Georgakakos A. (2001)

This study differ from the previous ones in that instead of looking at the climate change impacts of the California system as a whole, focus on just one reservoir, the Folsom Lake in the American River. Yao and Georgakakos (2001) developed in this study an integrated forecast-decision system for this study and used it to assess the sensitivity of reservoir performance to various forecast-management schemes under historical and future climate scenarios. The assessments are based on various combinations of inflow forecasting models, decision rules, and climate scenarios.

The climate scenarios are based on historic and potential inflow realizations generated by the Canadian GCM assuming either a no increase in CO2 concentrations (control scenario) or a 1% annual increase of CO2 concentrations. The results from this GCM (Carpenter and Georgakakos 2001) under the 1% CO2 increase suggest that Central California will experience wetter and more variable climate. Table X summarizes the results of this paper. In this Table is shown the performance of Folsom Lake operations under both the CO2 control and 1% annual increase scenarios for various forecasting and operation decision methodologies. The results in this Table show that:

- A 1% increase in CO2 concentrations will imply an increase in Folsom's energy generation and revenue of 20-24%, spillage would increase by 65-80% and flood damage would in some cases, increase by more than 4.3 billion dollars.
- Operating Folsom Lake under a combination of improved forecasting models and adaptive decision systems could effectively mitigate the effects of climate change and even improve reservoir response.

Table 2-3. Folsom Lake operation's assessments for future climate scenarios

Decision-forecast scheme		Reliability	Energy (GWH)	Energy value (million $)	Spillage (BCF)	Min. flow violations (days)	Max. flood damage (million $)
Future climate (control CO2)							
Rule Curve							
	Analog ESP	Deterministic	610.5	55.67	16.85	0	0
	Perfect forecasts	Deterministic	610.72	55.69	16.83	0	0
DSS							
	Hydrologic ESP	50%	654	59.4	16.436	0	0
		90%	678.878	61.595	10.368	0	0
	GCM-Cond. ESP	50%	654.474	59.455	15.978	0	0
		90%	675.121	61.21	9.585	0	0
	Analog ESP	50%	651.72	59.249	16.821	0	0
		90%	679.192	61.547	8.766	0	0
	Perfect forecasts	Deterministic	706.256	64.15	7.789	0	0
Future climate (1% annual CO2 increase)							
Rule Curve							
	Analog ESP	Deterministic	745.24	67.87	27.98	0	0
	Perfect forecasts	Deterministic	745.56	67.9	27.98	0	0
DSS							
	Hydrologic ESP	50%	788.26	71.56	28.67	0	4275.2
		90%	839.48	76.08	18.06	0	219.9
	GCM-Cond. ESP	50%	797.83	72.4	26.78	0	4275.2
		90%	833.78	75.54	17.87	0	841.44
	Analog ESP	50%	786.41	71.43	29.22	0	4275.2
		90%	846.23	76.68	16.83	0	0
	Perfect forecasts	Deterministic	868.92	78.77	15.09	0	0

Note: The results in this table were obtained using both the heuristic rule curves and Folsom Decision Support System (DSS) and various forecast schemes including the operational forecasts, analog Extended Streamflow Prediction (ESP), hydrologic ESP, GCM-conditioned ESP, and perfect forecasts. The reliability parameter indicates the type of forecast information utilized by the decision system. The 'deterministic' and '50%' indications imply the use of a single sequence. For the ESP schemes, this sequence corresponds to the median trace. The '90%' indication implies the use of the full forecast ensemble and a probabilistic tolerance threshold of 90% for the reservoir level constraints. For a full definition of the decision tools and forecast models refer to Yao and Georgakakos (2001).

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IIIA. Choosing a water resources model for climate change studies in California

1. Introduction: the need of a water resources model and objectives for this research task

The analysis of the performance the California water system under hypothetic hydrologic scenarios like the ones associated with climate change, requires the aid of water resources models, also called reservoir system analysis models.[3] For this project in particular we need a water resources model that can be used to estimate both the existing reliability of supply for different users in the Central Valley and how this might change under various climate-change scenarios. This reliability of supply is defined at the tail quantiles of a probability distribution where the random variable can be expressed in several ways, including as the absolute quantity delivered or as the ratio of the quantity delivered to some norm such as the contract entitlement or the ET requirements of crops typically grown in the area. We can employ history to assess what had happened in the past, but to assess what might happen in the future we need a water resources model that represents the operation of the California water system. This model will use the new runoffs derived from climate change impact studies on the Central Valley hydrology to estimate water supplies throughout the system. This model should have at least the following features:

- Descriptive and not prescriptive spirit. We need a model that will tell us how the system behaves under current operation policies, not how it ought to behave. Optimization can enter the analysis once we understand well how the system does actually operate.

- Hydrologic flexibility. This means that the model should run with any sequence of hydrologic conditions and not be bounded by any historic period hydrologic conditions.

- Good representation of the system in terms of coverage (that includes most of the main agricultural areas), spatial resolution (ie., it is possible to distinguish users with different set of water supply conditions, such as different water districts) and current operation policies and constraints.

In the following section we present a comparison of three currently available models that were analyzed for this research task.

[3] There a different alternatives of these models. They can be either mere descriptors of the water system which they represent (*descriptive models*) or they can be prescribe the best rules by which a system should be operated (prescriptive models). They also can have or not mathematical programming tools implemented. In Appendix D.1 of this Attachment there is a brief description of the differences between water resources models that should be used as a framework for the next section.

2. Comparison of water resources models available for California: CALSIM, CALVIN and CVMod

Models of the California water resources complex system have been developed by the U.S. Bureau of Reclamation (USBR), the California Department of Water Resources (DWR) and academic communities. The most prominent earlier attempts are the USBR's Project Simulation Model (PROSIM) and the DWR's Simulation Model (DWRSIM). Both were *descriptive* models that simulated the operations of the Central Valley Project (CVP) and State Water Project (SWP) the major water projects in California. PROSIM was a traditional water balance approach with a monthly time step, to simulate a system represented by 50 nodes which include 11 reservoirs. Monthly streamflow data is input at 24 of the nodes for a 57-year (1922-1978) simulation period (Wurbs, 1996 and Sandberg and Manza, 1991). DWRSIM on the other hand evolved from a HEC-3, a U.S. Army Corp of Engineers (USACE) simulation model into a network flow programming model with a mathematical programming algorithm that assigns different relative priorities to different demand points, to the different components that make up a demand point, and allocated storage within a reservoir to specific demands, providing a better balance among the reservoirs in the system (Chung et al., 1989; Wurbs, 1996). More recently, there have been developed three models of the Californian water system. These models are[4]: (1) CALSIM-II developed jointly by DWR and U.S. Bureau of Reclamation; (2) CALVIN developed at U.C. Davis and; CVMod developed at the University of Washington. Appendix VA.2 presents a brief description of these three models. Table 3A-1 compares the major features of these models.

[4] Models not included in this analysis but that will be included in future steps are: Natural Heritage Institute WEAP model developed by David Purkey and the HEC-5 reservoir model developed by the U.S. Corps of Engineers for the flood control Sacramento and San Joaquin River Basins Comprehensive Study.

Table 3A-1. Comparison between three water resources models for California [1]

	CALSIM-II	*CALVIN*	*CVMod*
Basic categorization	Descriptive Simulation with mathematical programming algorithm.	Prescriptive Optimization.	Descriptive Simulation without mathematical programming algorithm.
System Representation			
Coverage	All Central Valley plus SWP-CVP contractors in the San Francisco Bay, the Tulare Basin and Southern Californian.	The same as CALSIM-II plus Colorado River, all the Tulare Basin and Mono Lake and Owens Valley.	Same as in CALSIM-II.
Demand Representation	Sacramento Valley: Demands are based on land-use and specified irrigation efficiencies for project and non-project users. Resolution is at the DSA[2] level with some specific ID[3] identified[4]. East San Joaquin: Demands are based on time-series of values for certain identified ID[5] SWP contractors south of the Delta: Time-series of values for each contractor CVP contractors south of the Delta: Time-series of values for groups of contractors	Agricultural demands are calculated with the Statewide Water and Agricultural Production Model (SWAP) based on land-use and irrigation efficiencies for different crops. The model includes 21 regions in the Central Valley and four regions in southern California. Specific users are lumped into these regions. Urban demands are estimated separately and the model considers specific demand nodes for these.	Demands are time-series values obtained from CALSIM-II input files. However, there are the following differences with CALSIM-II values. Sacramento Valley: Demands are based only on project users' contracts. There's no representation of non-project users. East San Joaquin: Some specific users in CALSIM-II are lumped together in CVMod SWP contractors south of the Delta: Contractors are lumped together CVP contractors south of the Delta: Contractors are lumped together

	CALSIM-II	CALVIN	CVMod
Groundwater consideration	There is a representation of both groundwater pumping and groundwater-stream interaction. This representation is based on the results of CVGSM an integrated surface and groundwater model of the Central Valley[6].	There is a representation of both groundwater pumping and groundwater-stream interaction. This representation is based on the results of CVGSM an integrated surface and groundwater model of the Central Valley.	There's no representation of neither groundwater pumping nor groundwater and stream interactions.
Water releases and allocation decision	Reservoir releases and water allocation decisions throughout the system is made based on a mathematical programming approach that attaches different weights to different water users (including environmental instream uses) and storage levels. Carryover decisions for the CVP-SWP system are made based on fixed curves [7] that try to mimic historic deliveries for the period 1922-94.	After some environmental and institutional constraints are met, reservoir releases and water distribution decisions are made in such a way that the total cost associated with the final allocation of water is minimized.	Reservoir releases are based on detailed operation rules related to different levels on reservoirs (i.e. flood and conservation space) and environmental constraints. There's no further allocation procedure after water are released from the reservoirs.
Environmental Constraints	There's a very detailed representation of environmental constraints in the Delta and some stretches of rivers.	Environmental objectives are represented by time-series of minimum flow constraints on selected river locations and minimum flows to major wetlands taken from CALSIM-II studies results.	There is a representation of environmental constraints but not at the same level as in CALSIM-II.
Hydrologic foresight	The model does not have perfect foresight. It only knows current month inflows but uses forecasts (already prepared as time-series input files) of future inflows to decide deliveries.	The model has perfect foresight of the whole time-series of inflows. Release decisions are made based on that knowledge.	The model has no foresight beyond current month inflows. The model does not use either a forecast capability.
Hydrologic flexibility[8]	CALSIM-II is bounded to a series of 73 hydrologic years (1922-1994) that determine:	CALVIN is also bounded to the 73 time-series of hydrologic data because it uses as environmental constraints, output	CVMod is not bounded to any specific time-series of hydrologic data.

	CALSIM-II	CALVIN	CVMod
	• Water allocation decisions and carryover storage [(8)] • Water deficits/gains that are used to determine the DSA level hydrology. An alternative to this would require a precipitation/ runoff model coupled to CALSIM-II	data generated with CALSIM-II.	

Notes:

(1) Sources of information to develop this Table come from the models themselves and documentation when available. In the case of CVMod it also relies on personal communication with developers.

(2) DSA = Depletion Study Area

(3) ID = Irrigation District

(4) There's a proposed plan to update Sacramento Valley demand re presentation considered to have several flaws (DWR/USBR, 2004).

(5) Currently, the East San Joaquin region is being update to consider demands on a land-use base as in the Sacramento valley (DWR/USBR, 2004).

(6) There's an ongoing effort to update that groundwater representation in CALSIM-II considered deficient (DWR/USBR, 2004).

(7) These are called the WSI-DI-DELCAR set of curves (DWSR/USBR, 2002).

(8) By hydrologic flexibility we mean the ability of the model to perform studies with different time-series of hydrologic inputs. A flexible model is one able to use input data generated from example using synthetic streamflow techniques or streamflows derived from GCM models. An inflexible model is one that relies only on a fixed time-series of hydrologic data that at most can be modified applying constant (throughout the series) scaling factors.

(9) There's a DWR's project to change the allocation decision module in CALSIM-II for a more flexible one (CALSIM-II Allocation Model- CAM) that doesn't rely on past operation but is based instead on current reservoir operator's practices (DWR/USBR, 2004).

Based on the basic features of these three water resources models available and the need of our research project we have eliminated the use of the U.C. Davis-CALVIN model. The reason is that at this stage of the project we are interested in assessing the performance (reliability) of the Californian water system as is operated today considering both historic and climate change driven hydrologic inputs. The CALVIN model being a prescriptive model does not satisfy our needs because instead of describing the system as is operated today gives an optimistic view of "how" the system should be operated several constraints and barriers were lifted.

Besides having the ability of "describing" the California water system the model we need for our project should have the following features: (1) Hydrologic flexibility to allow the assessment of future "climate-change" hydrologic conditions; (2) Coverage of at least all the Central Valley and hopefully areas in Southern California; (3) Spatial representation hopefully at the Irrigation District level or in its defect at a spatial resolution that allows distinguishing users with different set of water supply conditions (i.e. different water sources and water rights) and; (4) Good representation of actual system policies and operations;. Just considering the two models analyzed here: CALSIM-II and CVMod we see in the following Table 3A-2, in which their strengths and limitations are compared, that none of them fulfills all these requirements although both can be improved (and in fact at least CALSIM-II is being improved in that respect) to achieve them.

Table 3A-2. Strengths and limitations of CALSIM-II and CVMod

	Strengths	Limitations
CALSIM-II	• "Good" representation of current operations/ environmental constraints. Appendix D.3 shows how the results of CALSIM-II and CVMod compare with historic operations of major reservoirs in the Central Valley.	• Hydrologic inflexibility • Not statewide coverage • Resolution not at the ID level as needed but better than in CVMod • Allocation/release procedure based on weights is more obscure for the user
CVMod	• Hydrologic flexibility • Allocation/release procedure based on rules gives transparency for the user	• Worse representation of current operations/environmental constraints. See Appendix D.3. • Not statewide coverage • Resolution not at the ID level as needed and worse than in CALSIM-II

Considering our needs for the research project in terms of the minimum features that a water resources model should have, we can draw the following conclusions about the three models analyzed so far:

- CALVIN model is not suitable for our needs because it's a prescriptive rather than a descriptive model.

- CALSIM-II in the other hand is a descriptive model with a very good representation of the system in terms of coverage, spatial resolution and current operation rules. The major fault of CALSIM-II is its inability to be run using a sequence of hydrologic inputs not strictly related to the 73 years of historic hydrologic inputs to which the model is bounded[5]. Another problem with CALSIM-II is its non-uniformity in terms of how water deliveries are set for different geographic areas. The good news for us is that inside DWR there is also concern for these two topics and there is an ongoing effort to improve both the "hydrologic flexibility" and the "system representation" of the model.
- Finally CVMod is also a descriptive model with unlike CALSIM-II an ability to be run by any hydrologic inputs (e.g. climate-change or synthetic generated inflows). The problem with CVMod is that some of the operation rules embedded in the model does not reflect the real system operation rules and hence the results of using this model could be far from how the system is actually being operated.

In conclusion there is no "A" model we can use for our purposes right now. All of them have some flaws that prevent us from using them without some modification. Given that we do not have the resources to develop a new water resources model for California, we can do the following. First of all there are still two more models we want to examine to determine whether they might be suitable for us. These are the NHI WEAP model and the USACE Res-Sim model developed for the Central Valley. A third alternative would be to discuss with DWR the status and perspectives of CALSIM-II development. A fourth alternative is to first modify CVMod to better reflect actual system operations and then use it. Specific work that could be done with the tools available are the following:

- Compare CALSIM-II reliability results (see next section) with real data. Check consistencies (e.g. sources of groundwater and non-project reliabilities).
- Use CVMod to study the new PCM3 and HadCM3 inflow scenarios
- Use CVMod do a series of what-if studies for the California System. The idea is by systematically changing inflows parameters (e.g. average and dispersion from the current statistical distribution) understand the reliability of the system for different targets.

In the next section we provide the results to date using CALSIM-II as a tool to measure Californian water system supply delivery reliability.

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[5] This bound ness is reflected in three areas of the model development:

- The DSA's water balance hydrologic setting that was performed to reflect history
- The carry over-deliveries decisions for the two projects (CVP-SWP) that are represented in a "step-function" that again was develop to mimic history
- And finally the forecasting procedure that in CALSIM-II is merely a timeseries of historic forecastings.

3. Results derived from the use of these models

As we presented in the last section there are two available models that represent the California Water System that satisfy somehow our needs for this project. The model we need should be able to assess the system performance at the Irrigation District level, in terms of water supply reliability under different hydrologic scenarios (e.g. current climate and future climate-change driven conditions). The following is a preliminary analysis of the reliability of the Californian water system under historic hydrologic conditions we have performed using CALSIM-II. As a future step in this research we will extend this analysis using CVMod in order to compare the results from these two models with what history can tell us about reliability in the system (see Chapter 5, Future Steps).

Assessing California water system reliability using CALSIM-II model

The most recent available simulations runs for CALSIM-II, known as the Benchmark Studies (DWR/USBR, 2002) contain monthly data for the demands and deliveries for different water users in the Californian water system. Using the available monthly data on demands and deliveries (only surface water deliveries) we calculated monthly and annual quantity-based reliability measures (eq 1) defined as the percentage of water delivered compared to a target delivery level represented by the water demand[6]. With both the monthly and annually reliability measures we constructed frequency curves of these values and calculated an overall reliability measure (eq 2).

Monthly/Annually quantity-based reliability measure

$$R_{ij} = 1 - \frac{(Demand_{ij} - Delivery_{ij})}{Demand_{ij}} \text{ if } Demand_{ij} \geq Delivery_{ij}\text{; if not } R_{ij} = 1 \quad (1)$$

Overall reliability measure

$$R_i = \frac{\sum_j \left(Demand_{ij} - Delivery_{ij}\right)^+}{\sum_j Demand_{ij}} \quad (2)$$

where i represent a certain user (or group of users) and j represents the corresponding timestep (month or year). The + sign denotes that only positive values are considered.

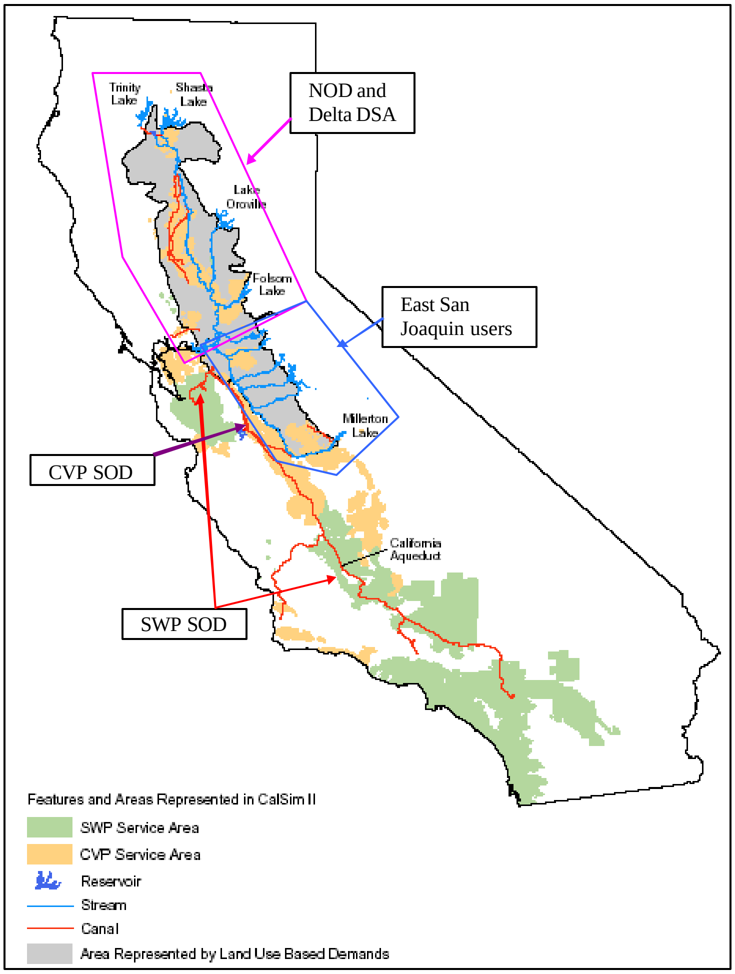
The analysis was done for different types of users according to their geographic location, their source of water and different water rights status. These different users were also aggregated into different levels. The first level considered the whole Central Valley

[6] This definition is based on Hashimoto et al. (1982) and Bogardi J.J. and Verhoef A. (1995). A time-base definition of reliability would be the fraction of time a system is unde r a no failure mode defined by a certain target. Other measures of a system performance not included in this analysis are the vulnerability and resilience (see Hashimoto et al (1982).

system[7]. The second level compared reliability measures for broad geographic categories of users: North of the Delta (NOD) Project and non-project users; State Water Project (SWP) South of the Delta (SOD) users; Central Valley Project (CVP) SOD users and East San Joaquin users. Figure 3A-1 shows a map of these broad categories of users. The third and final level went within some of these groups to asses the reliability for more specific type of users[8]. An example of the analysis done at this step was the comparison of the reliability among different types of CVP users SOD (i.e. Between Exchange, Agriculture, M&I and Refugee Contractors). Figure 3A-2 shows a schematic of how the different users in the Central Valley are classified into this different types and levels of aggregation. The overall reliability measure for each of these steps and time periods is presented in Table 3A-3. The reliability curves are presented in a series of Figures. These curves should be read first looking at a delivery target (say 50% of demand) in the ordinates axe and then at the percent of time this target is equaled or exceeded in the coordinates axe. Appendix D.4 contains a detailed explanation of the sources used to perform this analysis.

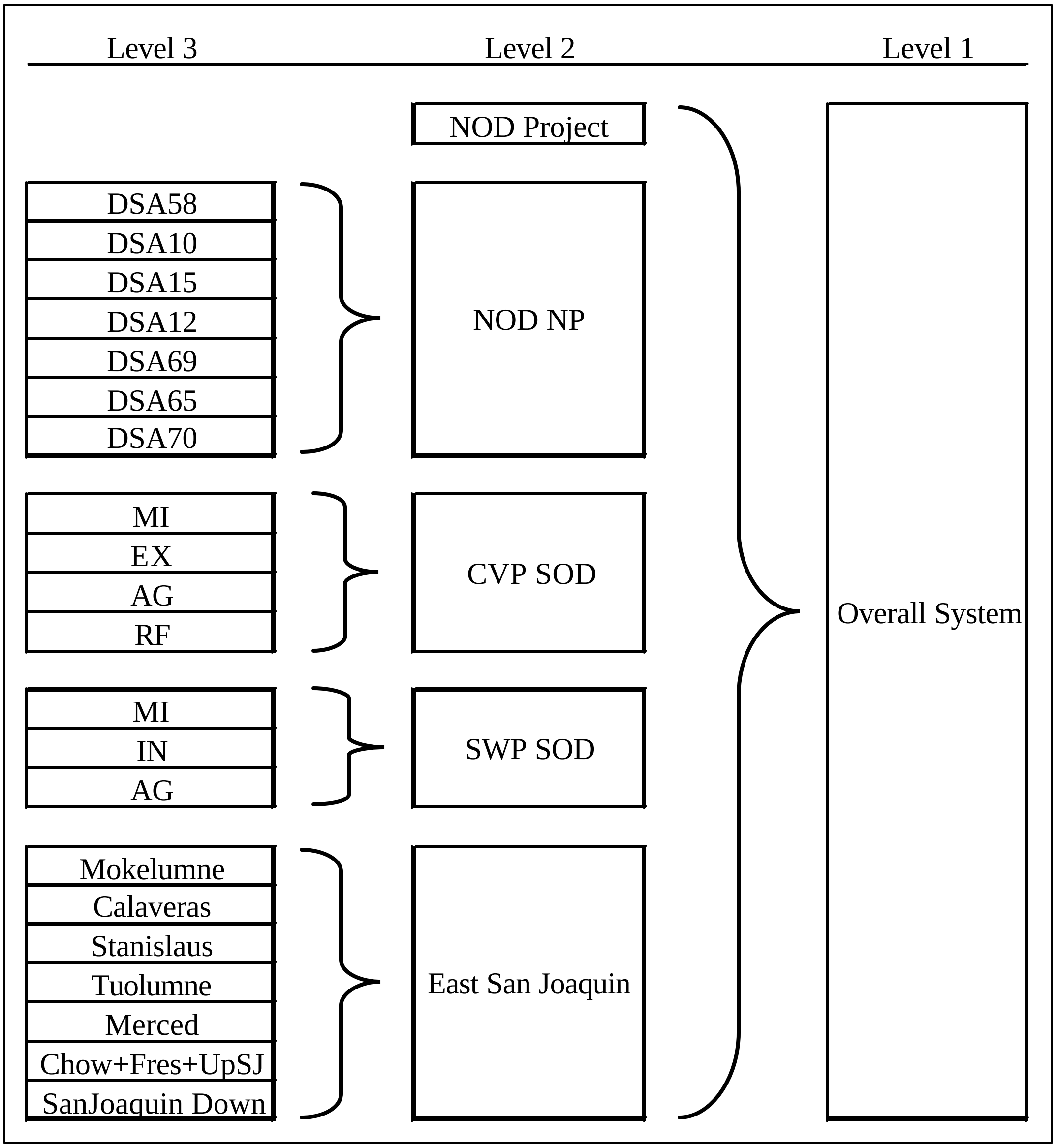
[7] Only Delta users were not considered in the analysis because there are some concerns about the corresponding CALSIM-II results that need to be discussed with the DWR.

[8] Using CALSIM-II it is also possible to a further step analysis of the reliability at the ID district level but there's not a good representation of these users yet so we preferred not to do it at this time.



Notes: NOD = North of the Delta; DSA = Depletion Study Areas; CVP = Central Valley Project; SWP = State Water Project

Figure 3A-1. Geographic location of users within CALSIM-II



Notes: NOD = North of the Delta; SOD = South of the Delta; DSA = Depletion Study Areas; CVP = Central Valley Project; SWP = State Water Project; AG = Agriculture Contractor; SC = Settlement Contractor; MI = M&I contractor; RF = Refugee Contractor; EX = Exchange Contractor

Figure 3A-2. Schematic showing group of users within CALSIM-II

Table 3A-3. Overall reliability measure of water supply deliveries for different water users in California

Analysis Performed	User	Annually	Monthly
Level 1:			
Overall System	NA	0.75	0.75
Level 2:			
Comparison of broad categories	NOD Project	0.80	0.80
	NOD NP	0.62	0.62
	CVP SOD	0.69	0.68
	SWP SOD	0.63	0.63
	East San Joaquin	0.84	0.84
Level 3			
Non-project users NOD DSA analysis	DSA58	0.87	0.87
	DSA10	0.48	0.48
	DSA15	0.94	0.94
	DSA10	0.33	0.33
	DSA69	0.83	0.83
	DSA65	0.33	0.33
	DSA70	0.85	0.85
CVP SOD	MI	0.87	0.87
	EX	0.97	0.97
	AG	0.65	0.63
	RF	0.97	0.97
SWP SOD	MI	0.81	0.80
	IN	0.12	0.12
	AG	0.80	0.79
Different East San Joaquin users	Mokelumne	1.00	1.00
	Calaveras	0.29	0.29
	Stanislaus	0.96	0.96
	Tuolumne	0.82	0.82
	Merced	0.87	0.87
	Chow+Fres+UpSJ	0.82	0.82
	SanJoaquin Down	1.00	1.00

Note: The numbers in the last two columns are very close because although the frequency of reliability values may differ as can be seen from the annual and monthly figures for each level of analysis (e.g. compare Figure 3A-5 with Figure 3A-6), the measure depicted in this Table (1- sum of deficits/sum of demands) could still be the same for both cases.

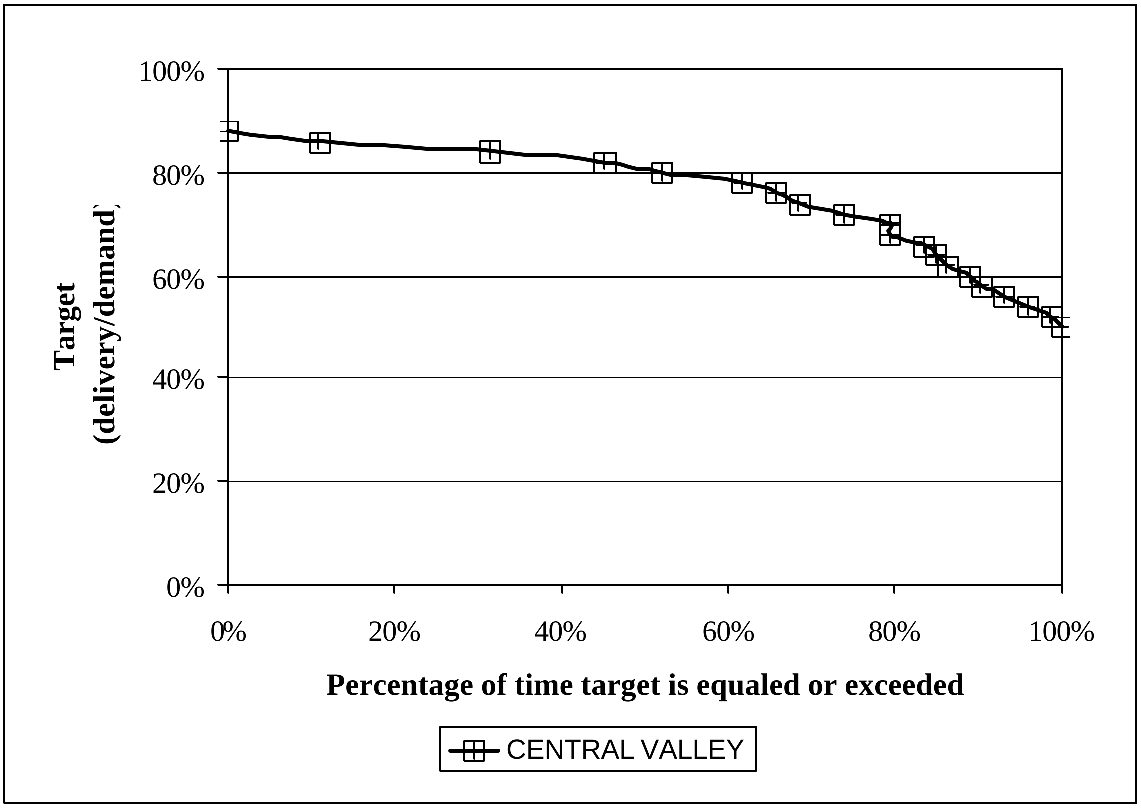


Figure 3A-3. Annual reliability for all users in the Central Valley

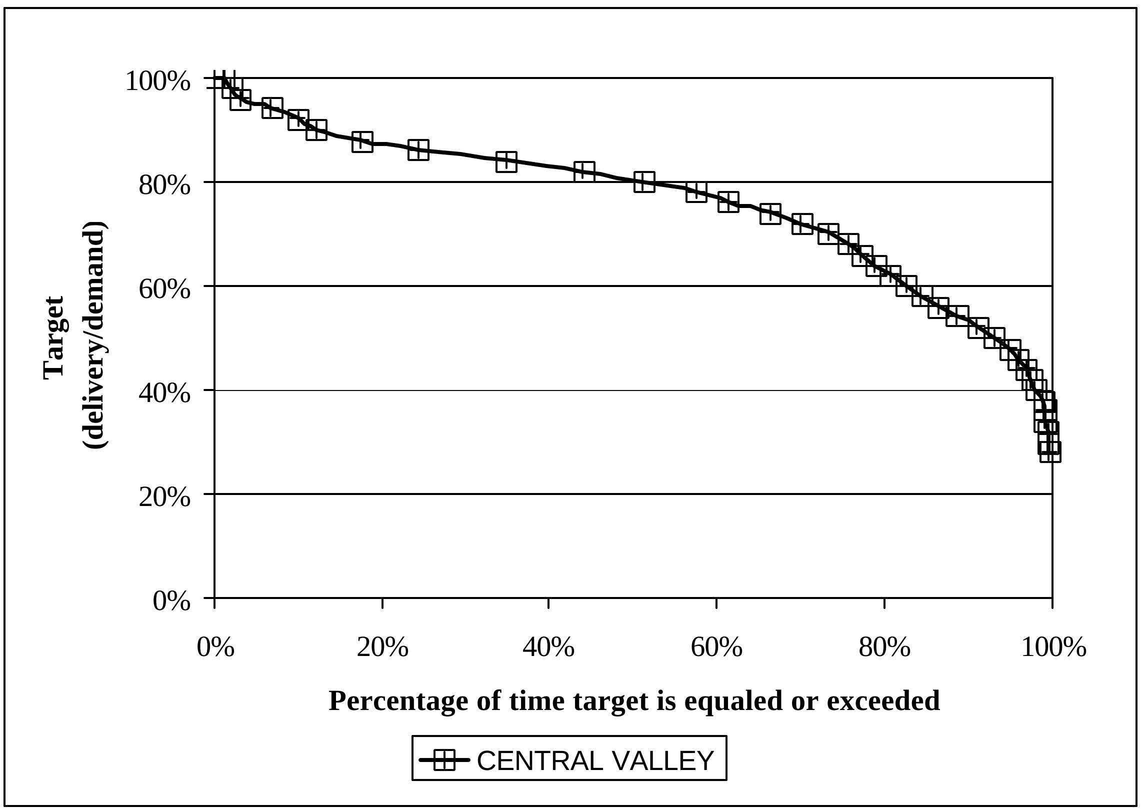


Figure 3A-4. Monthly reliability for all users in the Central Valley

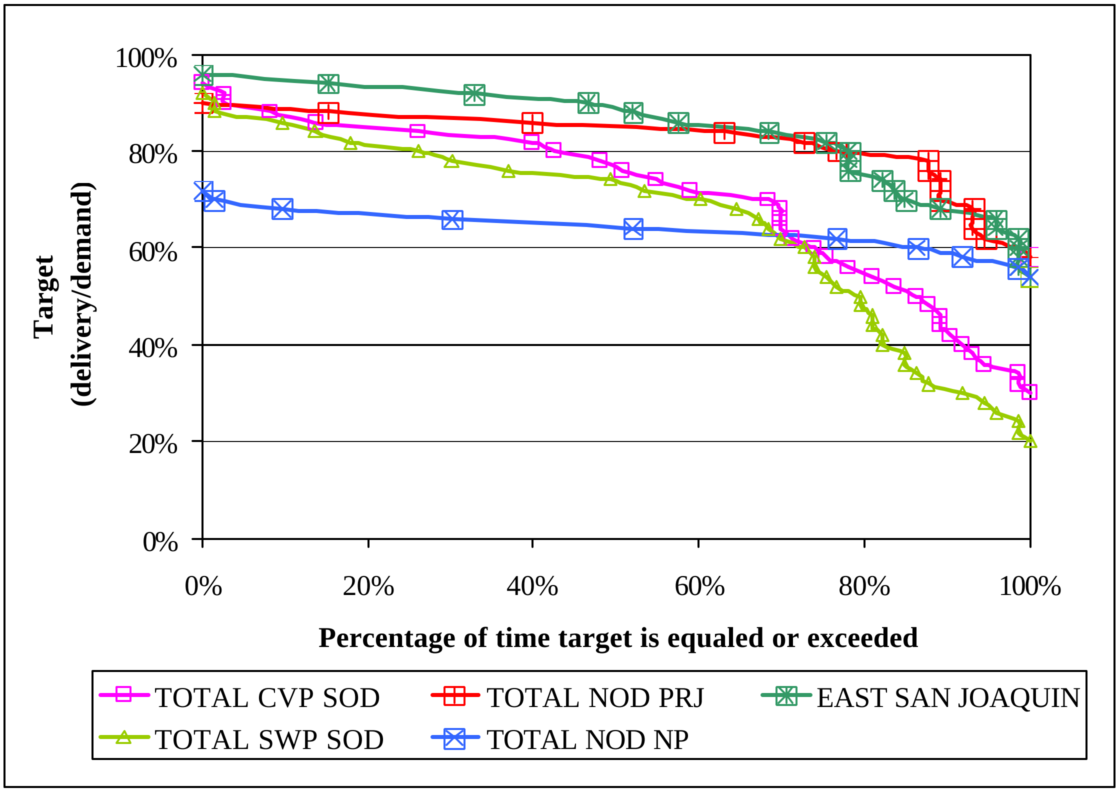


Figure 3A-5. Annual reliability for broad categories of users in the Central Valley

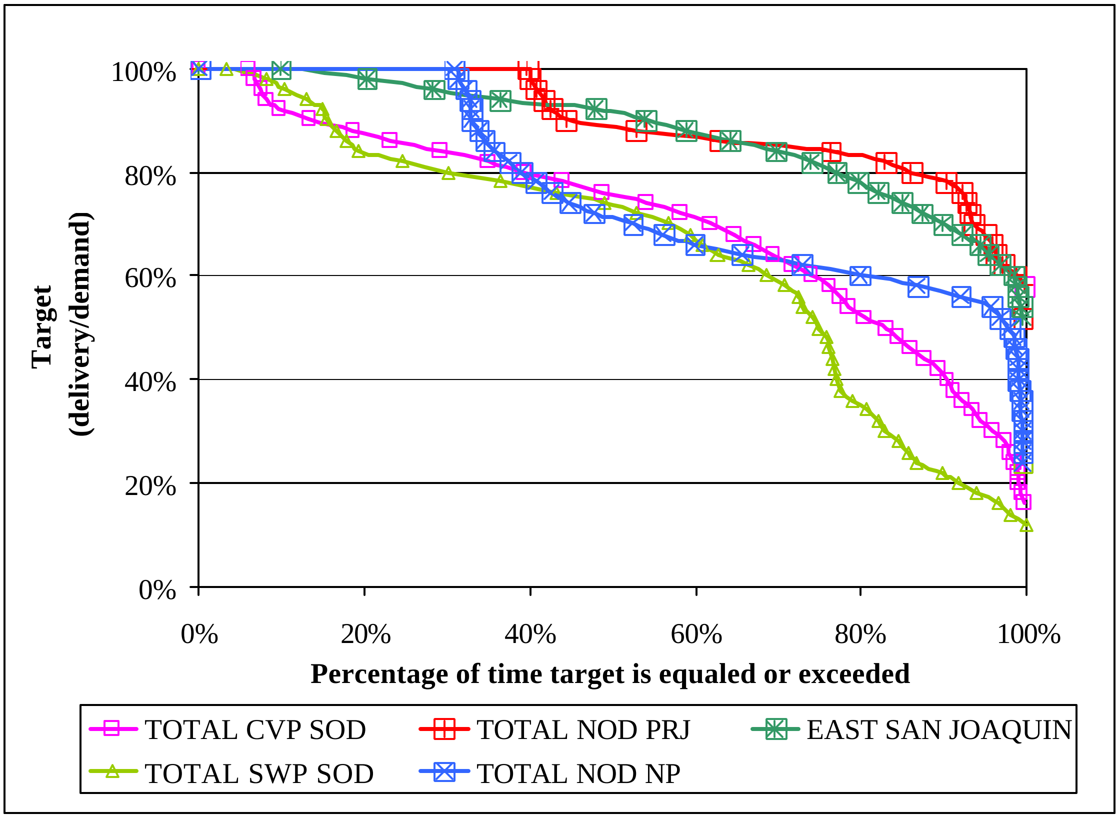


Figure 3A-6. Monthly reliability for broad categories of users in the Central Valley

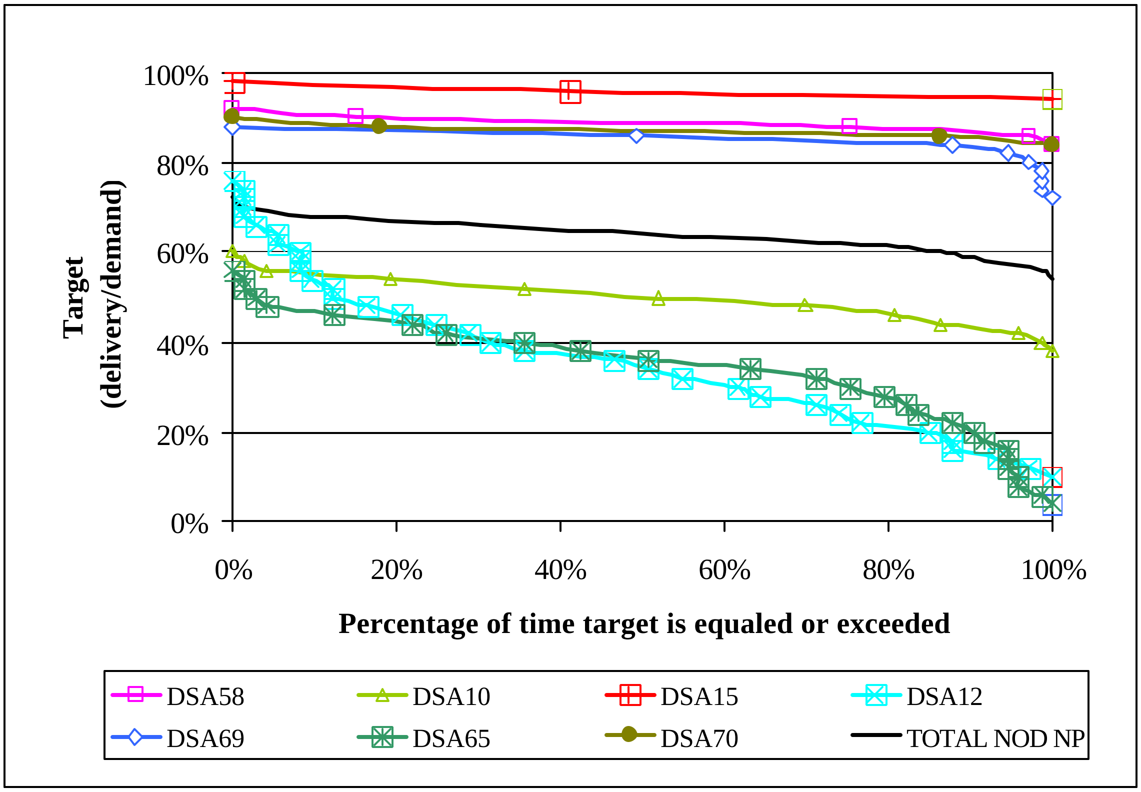


Figure 3A-7. Annual reliability for non-project users north of the Delta

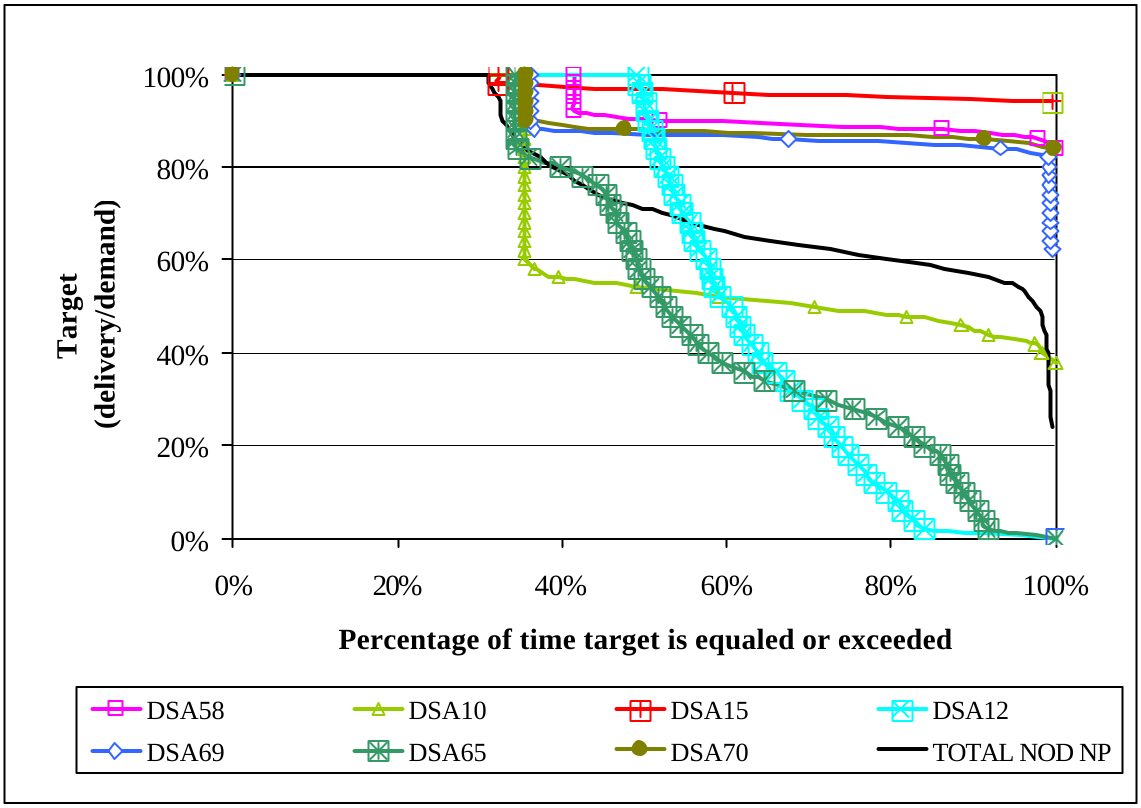


Figure 3A-8. Monthly reliability for non-project users north of the Delta

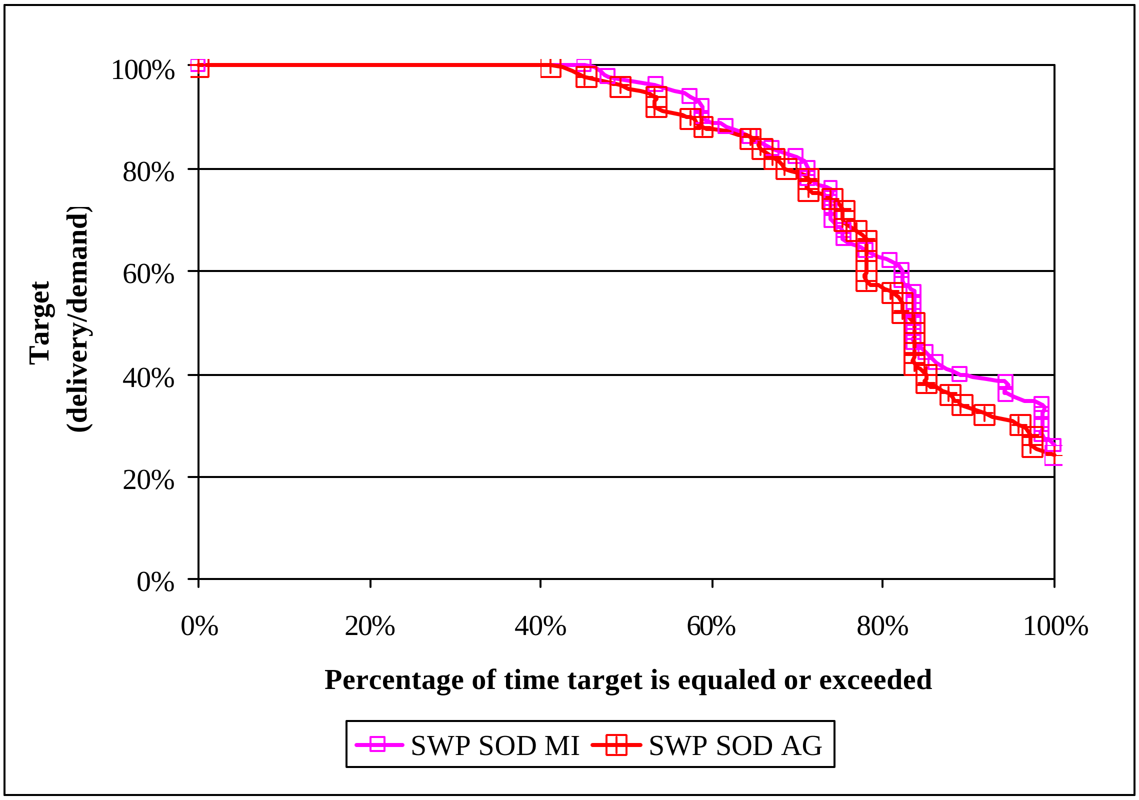


Figure 3A-9. Annual reliability for SWP contractors South of Delta

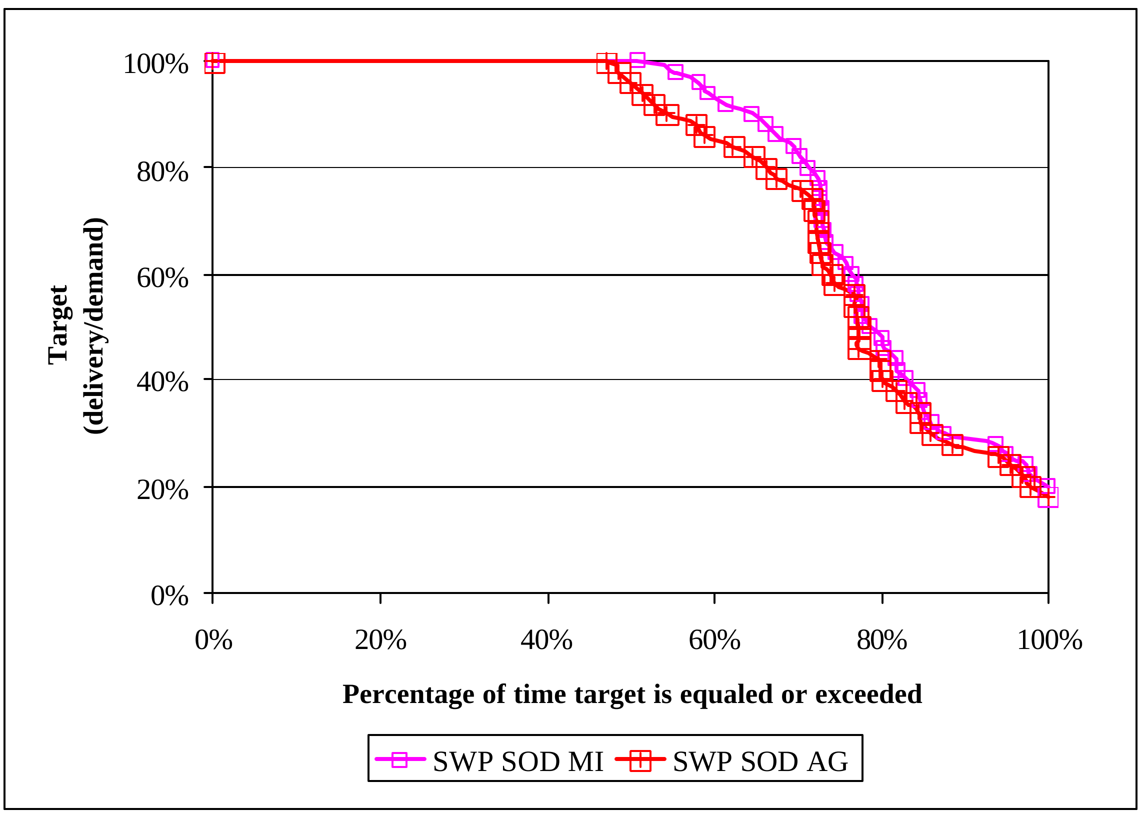


Figure 3A-10. Monthly reliability for SWP contractors South of Delta

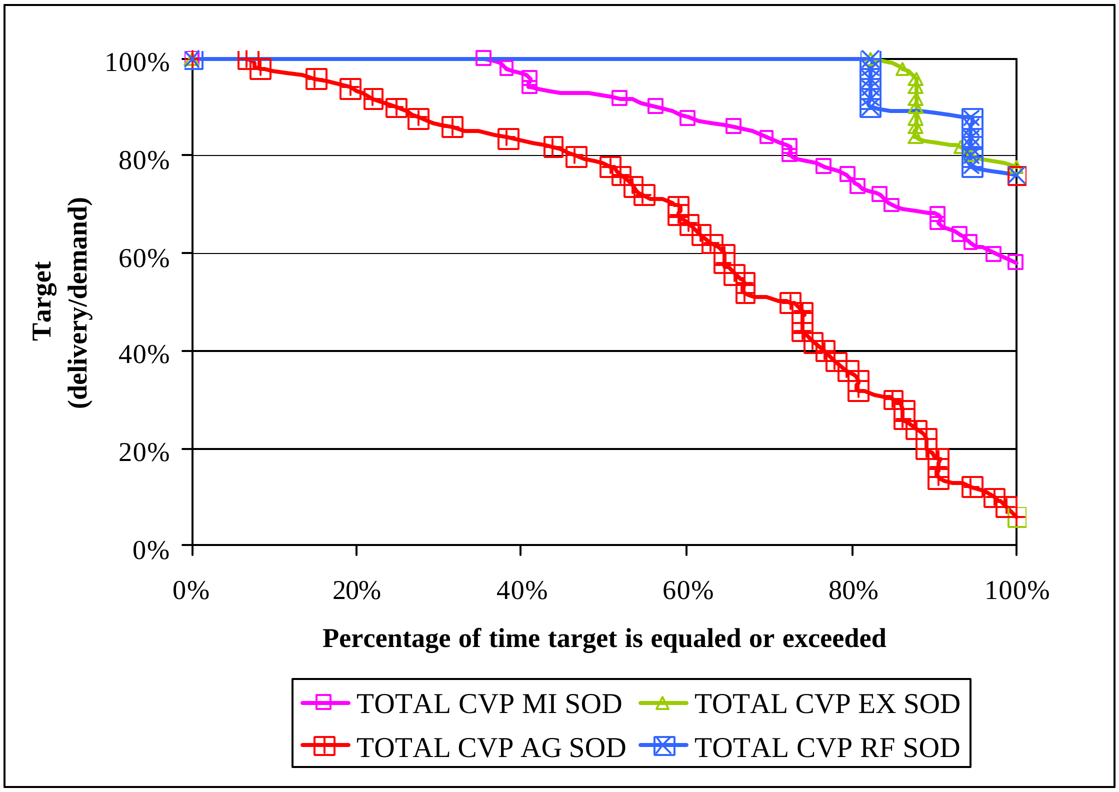


Figure 3A-11. Annual reliability for CVP contractors South of Delta

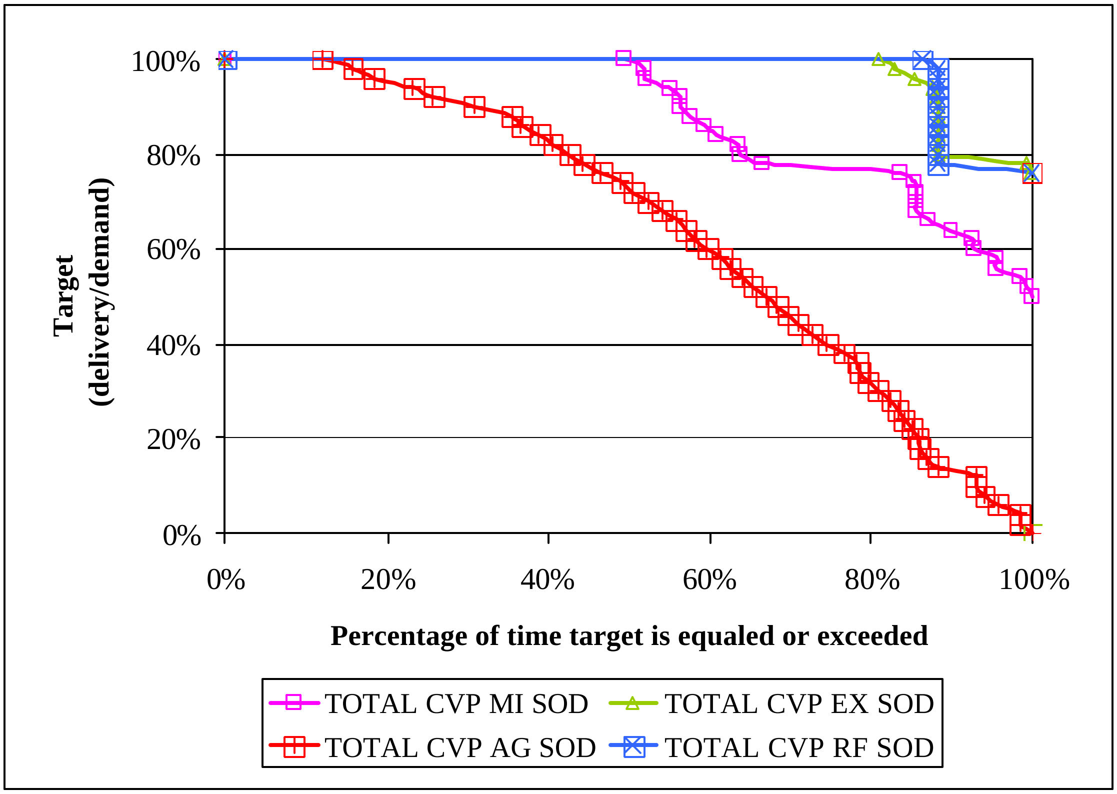


Figure 3A-12. Monthly reliability for CVP contractors South of Delta

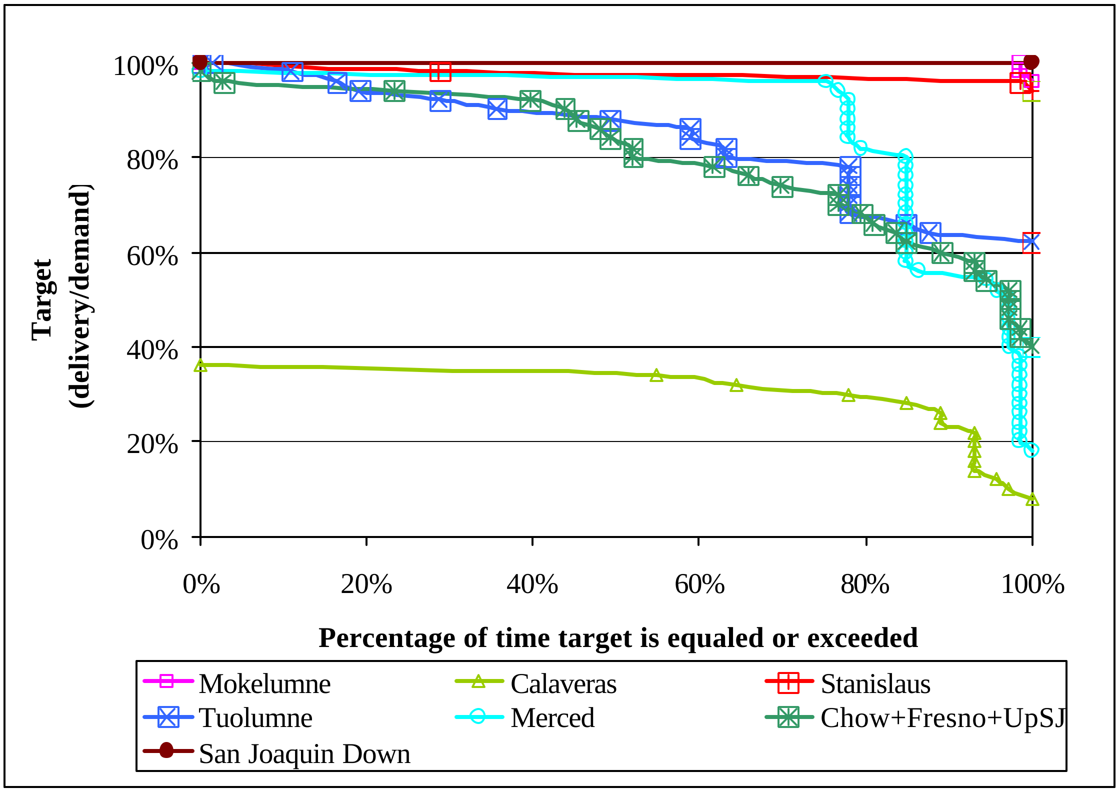


Figure 3A-13. Annual reliability for different East San Joaquin streams' users

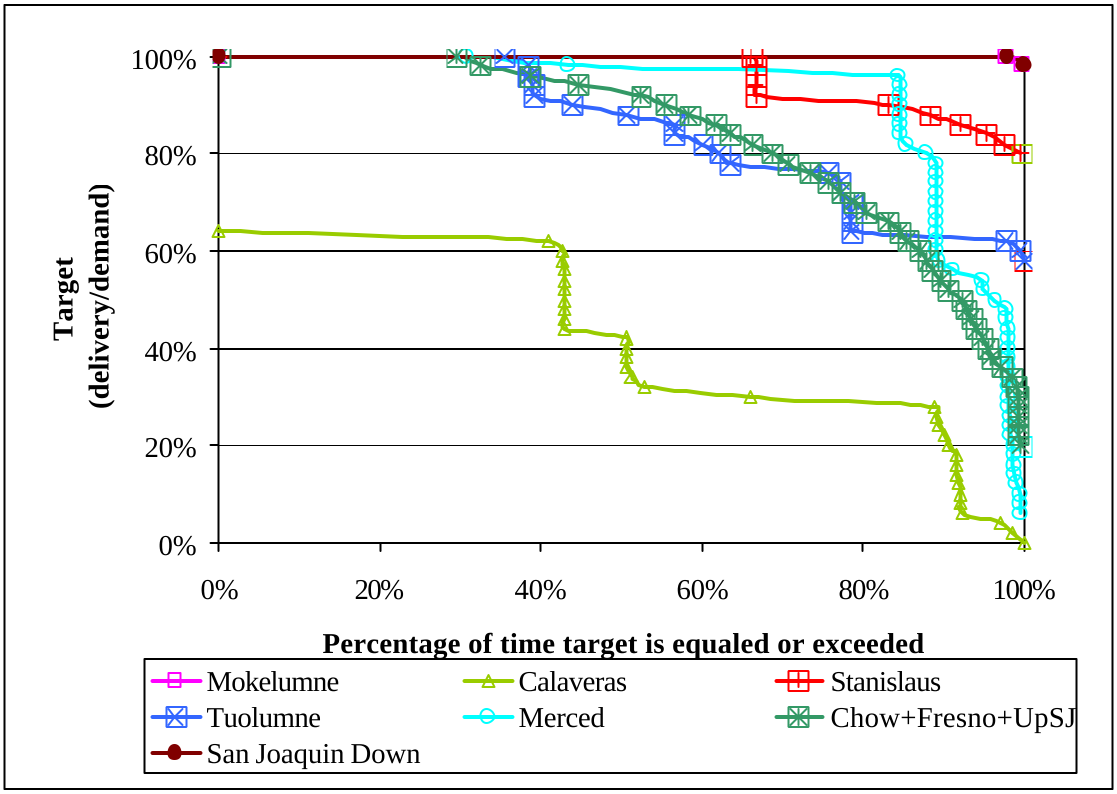


Figure 3A-14. Monthly reliability for different East San Joaquin streams' users

From the results presented in the previous figures, we can derive the following conclusions about water supply reliability in the Central Valley calculated using the results of the Benchmark CALSIM-II runs:

- The first and most important conclusion derived from this preliminary analysis is that water supply reliability is not the same among different water users in the Central Valley. This becomes clear when one compares the reliability for a group of users with the reliability of individual members within that group. Examples are the comparison between the reliability for all users in the Central Valley (Figures 3 and 4) and the reliability for the broad categories which constitute this whole group (Figures 5 and 6) or the comparison between NOD non-project users (included in Figure 3A-3 and 6) and the different DSAs where these non-project users are located (Figures 7 and 8).
- Another conclusion, derived when comparing the different pairs of figures, is that the distribution of reliability in annual terms is different than the distribution of reliability in monthly terms but they are quite similar when the overall measure of reliability is compared (Table 3A-3). The reason for this discrepancy is that the deficits in supply are concentrated in only *certain months* in the year, with the rest of the year (especially the winter months) being at 100% reliability. In the end we are interested in monthly reliabilities – especially those in the growing season. The annual reliability measures could hide the possibility that even though supply matches demand on an annual basis, within particular months of the growing season there is a shortage. This does not happen very often though as can be seen from the comparison of the monthly and annual results in Table 3A-3. For the future we might be interested in a monthly measure that takes into account the growing season portion of the year.
- As was expected different project contractors have different reliabilities according to their water right status. In this regard for example, CVP SOD Refugee and Exchange Contractors have a higher reliability of supply than M&I Contractors and these ones on the other hand have higher reliabilities than Agriculture Contractors (Figures 11 and 12). Something similar but more subtle arises with M&I and Agricultural SWP SOD Contractors (Figures 9 and 10).
- According to the results shown in Figures 3A-3 and 3A-4, when broad categories of users are compared the following is their order in terms of reliability: North of Delta Project users – East San Joaquin users – CVP SOD – SWP SOD – North of the Delta non-project users. An important caveat to this conclusion is that fact that within CALSIM-II demands are not estimated in a consistent way. Some places use land-use based estimates (all NOD users), while other consider pre specified timeseries of demands based on contracts (e.g. SWP SOD).
- The annual reliability curve for non-project users NOD (Figure 3A-3) show that water supplies for this group are mostly constant (between 60-70% of their demands) throughout the 73 years of different hydrologic conditions. CALSIM-II code delivers the other 30-40% of demands through unlimited groundwater

pumping capacity. If we examine the breakdown of this data between different geographic areas in the Sacramento Valley (different DSAs, Figure 3A-5) we can see that this 60-70% of reliability consists of some users having reliabilities in the order of 40% while others have around 90% reliability. The reason for these huge differences in reliability is not clear at this point. Some alternatives could be the proximity of the respective DSAs (see Figure 3A-13) to major sources of surface or groundwater (e.g. proximity to the Sacramento River) or the relative position in the basin (i.e. upstream users would have a more reliable supply than downstream users). On the other hand there is little confidence in the CALSIM-II results for non-project users in the Sacramento Valley because there is a misrepresentation of them in terms of sources of water. That is why DWR now recognizes the need to disaggregate the DSA structure in the Sacramento Valley to better represent the system (DWR/USBR, 2004). For this reason we will not pursue deeper analysis with these results at this moment.

- Finally there are also large differences in terms of reliability for different East San Joaquin users (DWR/USBR, 2004). But as in the previous case there is an ongoing effort to update the representation of this part of the system within CALSIM-II so we will not pursue further analysis at this point (Figures 13 and 14).

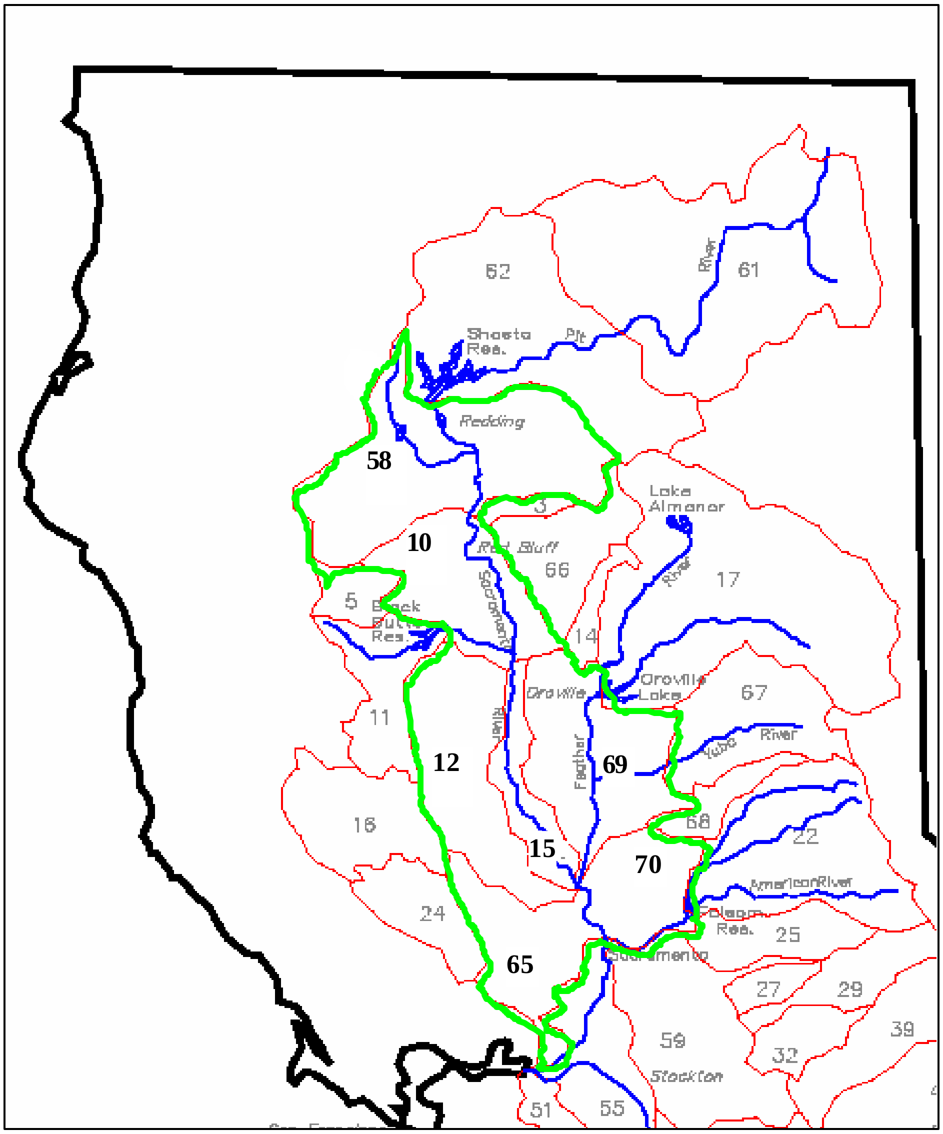


Figure 3A-15. DSAs represented in CALSIM-II (enclosed by polygons)

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Appendix IIIA.1. Brief framework on the differences of water resources models

The design, analysis, planning or operation of complex multipurpose, multiple-reservoir system like the California Central Valley System, requires the aid of water resource models or as they are also called reservoir system analysis models. There has been a lot of work on developing and applying reservoir system operation/analysis models during the past several decades. Yeh (1985), Wurbs (1985, 1993 and 1996) and Labadie (2004) provide a comprehensive, state-of-the-art review of these models. The following summary based greatly on those works will provide a framework for both describing and comparing the different reservoir system models developed for California.

Reservoir system analysis models have traditionally been categorized as either *simulation* or *optimization* models. A *simulation* model reproduces the essence of a system without reproducing the system itself to predict its behavior under a given set of conditions. From the perspective of reservoir system analysis, simulation models reproduce the hydrologic and/or economic performance of a reservoir system for given inflows and operating procedures (Wurbs, 1996). The models are based on mass-balance accounting procedures for tracking the movement of water through a reservoir-stream system and compute storage levels and discharges at pertinent locations in a stream-reservoir system for various sequences of hydrologic inputs (streamflow, rainfall, and evaporation) and demands for releases or withdrawals for beneficial purposes. Physical constraints, such as storage capacities, outlet and conveyance facility capacities, and institutional constraints, such as maintenance of flows associated with downstream water rights, are also reflected in the models (Wurbs, 1985). Alternative runs of a simulation model are made to analyze the performance of the system under varying conditions, such as for alternative operating policies (Wurbs, 1996). On the other hand an *optimization*[9] model refer to a mathematical formulation in which a formal algorithm is used to compute a set of decision-variable values that minimize or maximize an objective function subject to constraints. For a reservoir system problem the decision variables are typically release rates end-of-period storage volumes and allocation of water throughout the system. The objective function may be a mathematical representation of a planning or operational objective, or may be a penalty or utility function used to define operating rules based on relative priorities (Wurbs, 1996). The generally accepted method for determining the objective function (system's performance) has been one of economic impact. Either the total cost of the system is minimized or the total economic benefit of the system is maximized. Constraints typically reflect mass balances, storage capacities and other physical characteristics of the reservoir-stream system, diversion or streamflow requirements for various purposes and mass balances (Wurbs, 1993). Optimization techniques can be divided into three distinct categories: (1) linear programming, (2) dynamic programming, and (3) nonlinear programming.

[9] The term *optimization* is used synonymously with *mathematical programming*.

Some of other major differences between *simulation* and *optimization* approaches are summarized in Table 3A-3.

Table A-3A-1. Some differences between Simulation and Optimization models

	Simulation Models	*Optimization Models*
Operating rules	A simulation models needs detail specification of operating rules	Many optimization models compute the releases that optimize an objective function without directly using detailed operating rules, not providing generally mechanisms for the user to define the operating rules in greater detail.
System representation	A simulation model permits a more detailed and realistic representation of the complex characteristics of a reservoir/river system (e.g. nonlinearities) providing greater modeling flexibility and versatility.	An optimization model usually requires assumptions and simplifications (e. g. linearization) on model structure and system constraints for practical implementation
Major hurdle to overcome	Simulation studies are only useful if the operating policies incorporated in the simulation realistically reflect actual or potential system operation.	Defining system objectives, developing criteria for quantitatively measuring system performance in fulfilling the objectives, and handling interactions and conflicts between objectives is a major area of complexity in developing optimization models.
Finding the optimal policy	Within a simulation approach there is often a frustratingly large number of feasible solutions and plans. It takes an enormous computational effort to select a solution that might still be far from the best possible	Optimization models automatically search for an "optimum" set of decision variable values looking at (implicitly) all possible decision alternatives
Foresight	Simulation models perform computations period by period in such a way that future streamflows are not reflected in release decisions, except for some models which include features for limited short-term forecasts.	Optimization models typically make all release decisions simultaneously, considering all streamflows covering the entire hydrologic period of analysis.

Sources: Wurbs (1993), Yeh (1985)

Although optimization and simulation are two alternative modeling approaches with different characteristics, the distinction is somewhat obscured by the fact that many models, to varying degrees, contain elements of both approaches. All optimization models somehow also “simulate” the system and some of the simulation models have mathematical programming algorithms that derive the operating rules although the model it’s still a representation of actual operations and not “optimal” operations[10] (Wurbs, 1996). Simulation and optimization models can also be used in combination to analyze a certain reservoir system.

Another useful way of categorizing reservoir systems models that pertains more to the general modeling orientation is to classify them as being either *descriptive* or *prescriptive* models. A *descriptive* model is a representation of a system used to predict its behavior under a given set of conditions, i.e. it will demonstrate what will happen is a specified plan is adopted. On the other hand *prescriptive* models determine the plan (e.g. operating policies) that should be adopted to satisfy decision criteria (e.g. cost minimization) (Wurbs, 1996). Simulation models are in essence descriptive models, but optimization models that incorporate mathematical programming algorithms to automatically search for an optimum set of decision variable values may be either descriptively or prescriptively oriented. An example of the former are the network flow programming models[11].

Considering this two model classifications and based on Wurbs (1996) we categorize for future use reservoir system analysis models as:

- Descriptive simulation models that use no mathematical programming algorithms
- Descriptive simulation models based on mathematical programming
- Prescriptive optimization models

[10] An example of this later case are the network flow programming models that have proven to be of practical application in reservoir system analysis. In a network flow model, the system is represented as a collection of nodes (location of reservoirs, diversion points, stream tributary confluences, etc.) and arcs (river stretches, canals, etc.). Each arc (and storage levels) would have associated a cost or penalty (specified by the user) and an optimization algorithm would distribute the flows in order to minimize the costs associated with the different arcs.

[11] Ibid.

Appendix IIIA.2. Brief description of CALSIM-II, CALVIN and CVMod water resources models

CALSIM-II [12]

CALSIM-II is a network flow programming model developed jointly by the DWR and U.S. Bureau of Reclamation to represent the joint CVP–SWP water supply delivery system[13]. CALSIM-II routes the water in the system on a monthly basis using an integer-linear-programming solver of operational decisions that minimize a priority-based penalty function of delivery and storage targets. Calibration of the weights of these penalty functions train the model to adhere to operating rules and constraints such as fish flow requirements, downstream water quality objectives and contract deliveries to agricultural and urban water districts. The end-of-period storages from each optimization step are used as the initial conditions for the next month's optimization. Between months, nonlinear simulation-style adjustments can be made to reflect more complex environmental regulations, groundwater dynamics, etc. Model output includes monthly reservoir releases, river flows, reservoir stored water volumes, 'Delta' export activities, and indicators of Delta water quality conditions. A baseline version of the model called Benchmark Studies (DWR/USBR, 2002) was set up to perform monthly operations decisions for a 73-year simulation period that is referenced to 1922 through 1994 hydrologic years experienced in the Central Valley. Water demands and system infrastructure are modified to represent a year 2001 and 2020 level of development. This Baseline model is available in several versions, representing different subsets of state and federal regulations. The model focus mostly on the Sacramento and San Joaquin Valley systems with some representation of surface deliveries to the Tulare Basin and Southern California urban areas but does not include sources of water like the Colorado River or the Mono Lake basin.

CALVIN [14]

The CALVIN (**Cal**ifornia **V**alue **I**ntegrated **N**etwork) model was developed at U.C. Davis. The model is a *prescriptive optimization* model that operates surface and groundwater resources and allocates water over the historical hydrologic record maximizing the economic values of agricultural and urban water use statewide, within physical, environmental, and selected policy constraints (Draper et al, 2003). CALVIN schematic includes the entire Central Valley, the Trinity River system reservoirs, parts of the San Francisco Bay, southern California SWP contractors, water users of California's portion of the Colorado River and the Owens Valley and Mono Basin and finally groundwater sources of water, making CALVIN the model with the broadest coverage of water users in California. This optimization problem in CALVIN is solved using the USACE Hydrologic Engineering Center's *HEC-PRM* software, which uses a network solver. Monthly operation and allocation decisions within the optimization problem are

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[12] Description based on Munevar and Chung (1999), Brekke et al (2004) and Quinn et al. (2004).

[13] CALSIM-II replaced the previous agencies models: PROSIM, DWRSIM and SANJASM.

[14] Description based on Draper et al (2003).

made for a 72-year period based on the 1922–1993 hydrologic period with perfect foresight of future inflows.

<u>CVMod</u> [15]

CVMod (**C**entral **V**alley **Mod**el) is a simulation model developed at the University of Washington, Seattle. The model operates at a monthly timestep and represents the major projects and operational features of the Sacramento–San Joaquin basin. CVMod simulates the movement and storage of water within the basin given current operational policies. The primary hydrologic input to CVMod is monthly streamflow, which comes either from observed naturalized streamflow (for studies of past climate) or from the VIC simulations[16]. The model's outputs are reservoir levels and releases, from which the predicted performance of the system can be calculated. CVMod runs on STELLA a commercially available object-oriented modeling package designed to simulate dynamic (time-varying or otherwise changing) systems characterized by interrelated components (Wurbs, 1996).

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[15] Description based on Vanrheenen et al (2004).

[16] VIC (Variable Infiltration Capacity) is a regional hydrologic model implemented for the San Joaquin-Sacramento basins (Vanrheenen et al, 2004).

Appendix IIIA.3. Comparison of CVMod and CALSIM results with historic DWR data

The purpose of this Appendix is to compare the performance of the two water resources analyzed in this project; CVMod and CALSIM-II. To assess the models performance we compared the results derived from historic runs of these models, expressed as end of month storage level for major reservoirs in the Central Valley, with the historic data available from DWR website. The period of analysis was 10/1979 through 6/1994.

In Table 3A-2 and Figures 16 through 37 we present the results of this comparison. Table 3A-2 presents for each of the reservoirs considered in the analysis:

- average end of month storage derived for both models and the historic data
- average deficit/surplus for data coming from both models as compared to historic data
- standardized deficit/surplus (i.e. deficit/surplus divided by average historic data)
- sum of squares of the deficits/surplus divided by average historic data (standardized)
- correlation between models and historic data

Then Figures 16 through 37 present for each reservoir first the timeseries of end of month storages according both with the models run results and historic data and then the standardized deficits/surplus (i.e. deficit/surplus divided by average of historic storage).

Examining these results it can be seen that although, none of the models is really accurate to represent historic storages in the reservoirs in the Central Valley, CALSIM-II overall perform better than CVMod. It has both lower storage deficits, expressed as the standardized sum of square errors, and higher correlation with historic data (compare columns 7 with 10 and 11 with 12 in Table 3A-2) for most of the reservoirs in the Central Valley. The reasons for these differences are not clear at this point. Some alternative candidates are the following:

- The fact that the models are run considering a constant level of development (2001 in this case) that does not represent historic levels of development might induce differences in storage levels. This factor could explain why both models differ from historic data but no why they differ from each other. What could explain these differences though is the fact the CALSIM-II uses variable (throughout the years) demand while CVMod uses constant demands.
- Another reason why CVMod is not following as close as CALSIM-II reservoir rules and operations could be the fact that the reservoirs in CVMod are not allowed to draw water below their conservation bottom level which in actual operations do actually happen.

- And a final reason could be the lack of any forecasting capability within CVMod, unlike CALSIM-II, which relies on the historic forecasting procedure to determine how much water to deliver or to store for carry over.

Table A-3A-2. Comparison between CVMod and CALSIM results and DWR historic data on reservoirs storage in the Central Valley (1)

Reservoir	DWR data Average	CVMod Average	CALSIM Average	CVMod Average Deficit	CVMod Std Deficit (2)	CVMod Std Square deficits (3)	CALSIM Average Deficit	CALSIM Std Deficit (2)	CALSIM Std Square deficits (3)	CVMod Correl. (4)	CALSIM Correl. (4)
Shasta	3005	1605 (5)	2895	-1399	-0.47	***48***	-110	-0.04	***2***	0.59	0.94
Trinity	1739	1403	1391	-336	-0.19	***10***	-348	-0.20	***10***	0.89	0.90
Whiskeytown	220	223	224	3	0.01	***1***	4	0.02	***1***	0.79	0.80
Oroville	2456	2874	2371	418	0.17	***9***	-85	-0.03	***4***	0.82	0.88
Folsom	588	497	533	-91	-0.15	***21***	-54	-0.09	***9***	0.64	0.82
San Luis CVP	544	606	520	62	0.11	***29***	-24	-0.04	***29***	0.74	0.73
San Luis SWP	710	517	526	-193	-0.27	***41***	-184	-0.26	***52***	0.61	0.53
Camanche/ Pardee	421	422	444	2	0.00	***4***	23	0.05	***2***	0.90	0.94
New Hogan	117	95	109	-22	-0.19	***15***	-8	-0.07	***4***	0.93	0.98
New Melones	1039	926	1323	-113	-0.11	***55***	284	0.27	***69***	0.61	0.62
New Melones	1184	857	1231	-327	-0.28	***21***	47	0.04	***6***	0.89	0.94
New Don Pedro/ Lake	1872	1822	1929	-50	-0.03	***4***	57	0.03	***1***	0.92	0.97

Notes:

(1) For the period 10/79 - 6/94

(2) Equals to the average of the deficits divided by DWR average data

(3) Equals to the sum of deficits squared divided by DWR average data

(4) Correlation between model data and DWR data

(5) We are not confident at this point about the CVMod results for Shasta reservoir. We're checking with the model developers at U. of Washington why there is such a difference between CVMod and historic storage results. One alternative answer could be the different run period used in this analysis and the one (much longer) used in the calibration of the model 2 years ago (Nathan Vanrheenen, U of Washington, personal communication).

(6) Most of the deficits for New Melones come from the first or two years where both CVMod and CALSIM reservoirs start with considerably more water stored than DWR historic data. These results are consistent with the fact that New Melones was built in 1978 and that CVMod uses as initialization data CALSIM -II data running on a longer period of time. This is the reason why we present a separate set of results only including data from 3/82 when the reservoir was filled.

Sources:

CVMod results: 03-04 version, CALSIM Historic run, 2001 LOD

CALSIM results: Sep 01, Benchmark Studies D1641, 2001 LOD

DWR data: CDEC website, http://cdec.water.ca.gov/misc/resinfo.html

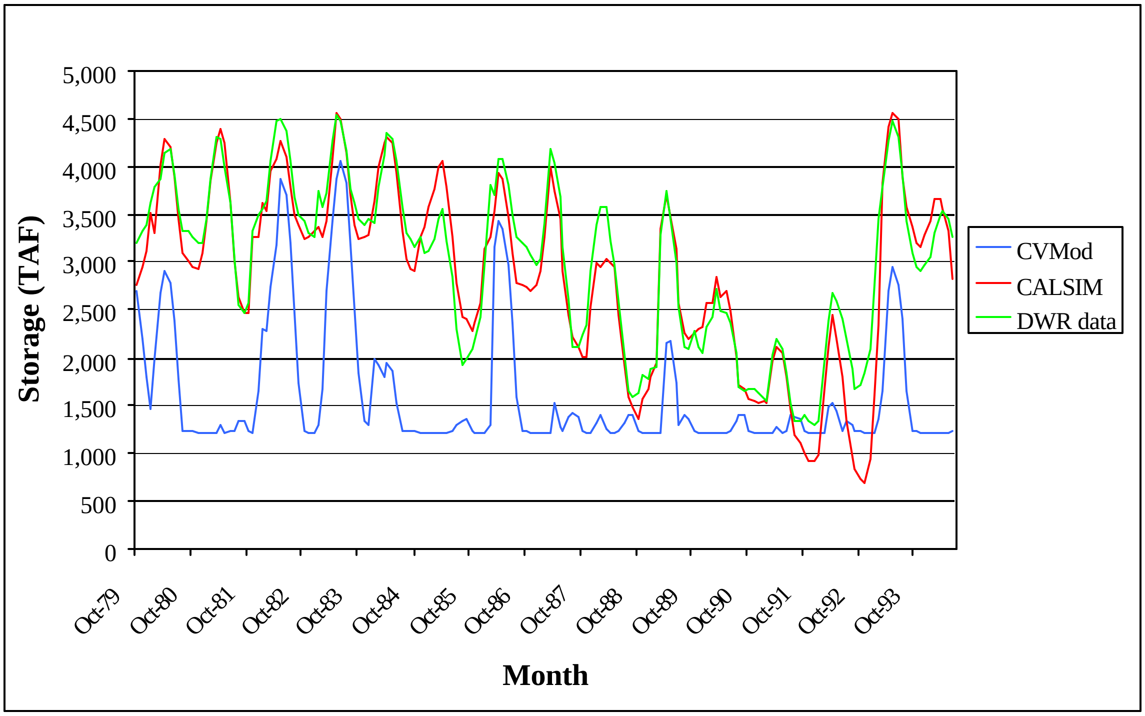
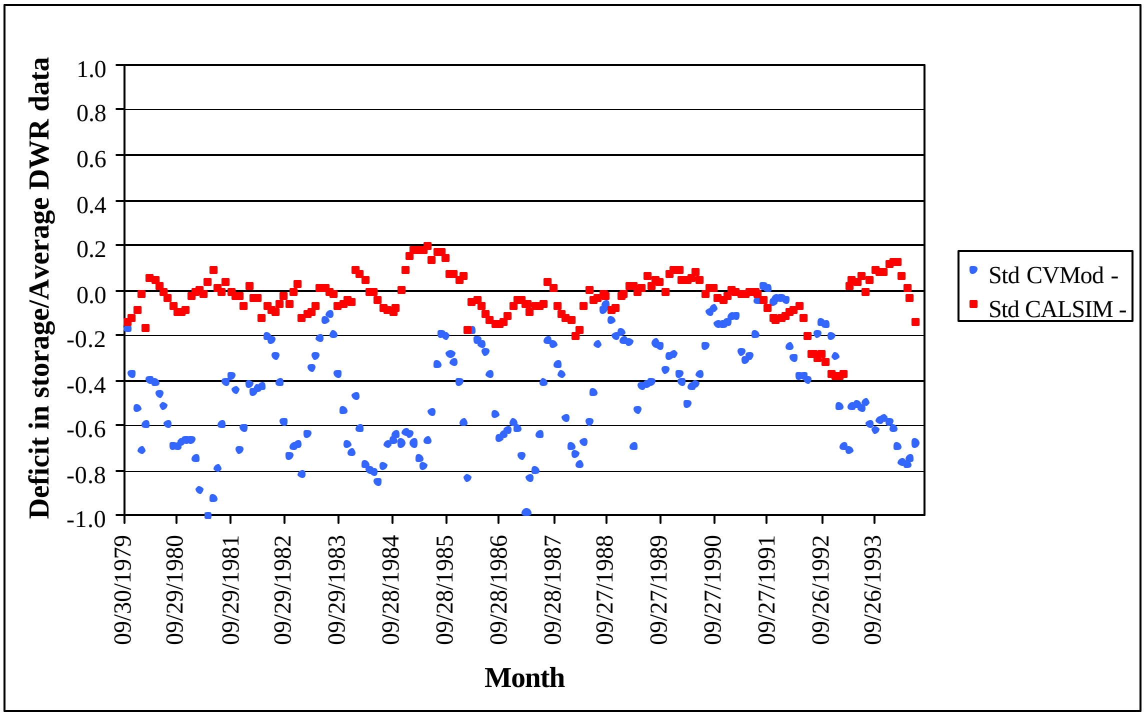


Figure A-3A-1. Comparison of end of month Shasta storage levels



Standardized Deficit/Surplus = (Model Result – DWR historic data) / Average of DWR historic data

Figure A-3A-2. CALSIM-II and CVMod standardized deficit/surplus in Shasta storage level compared to historic data

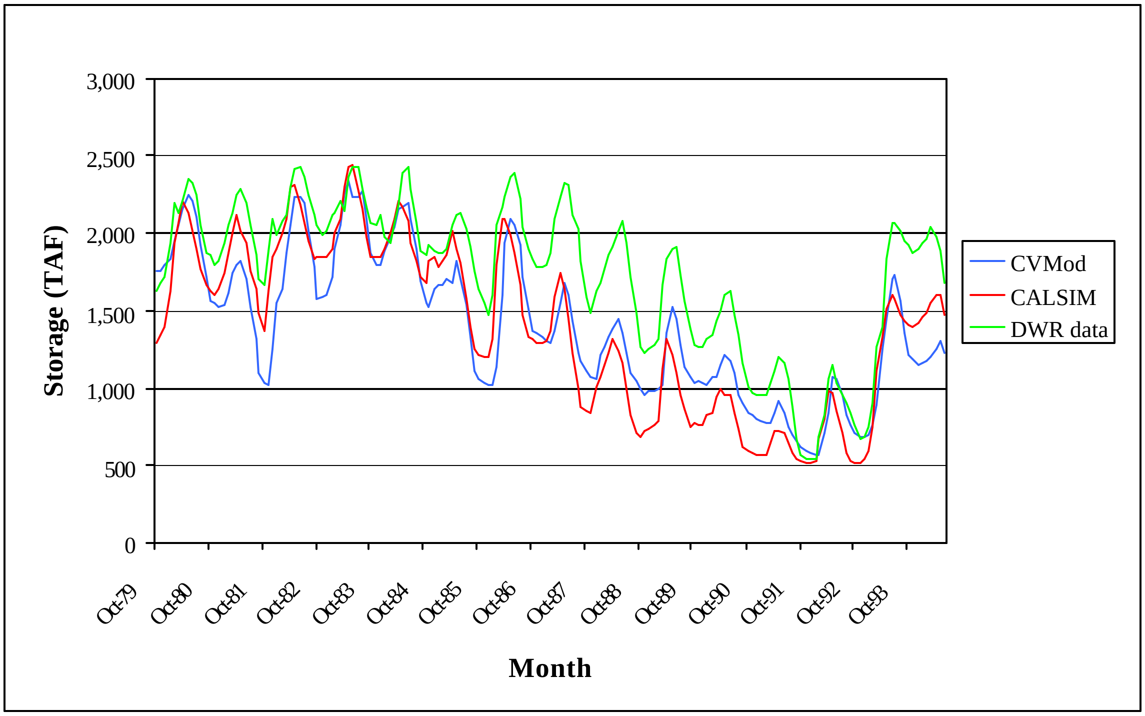
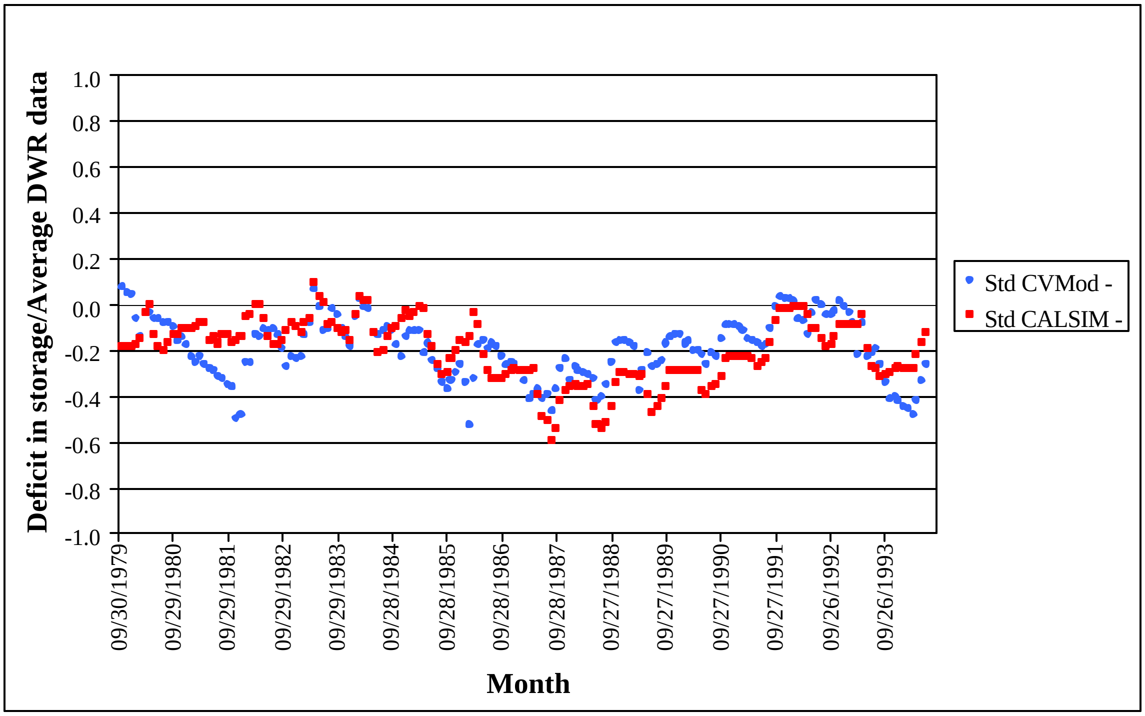


Figure A-3A-3. Comparison of end of month Trinity storage levels



Standardized Deficit = (Model Result – DWR historic data) / Average of DWR historic data

Figure A-3A-4. CALSIM-II and CVMod standardized deficit/surplus in Trinity storage level compared to historic data

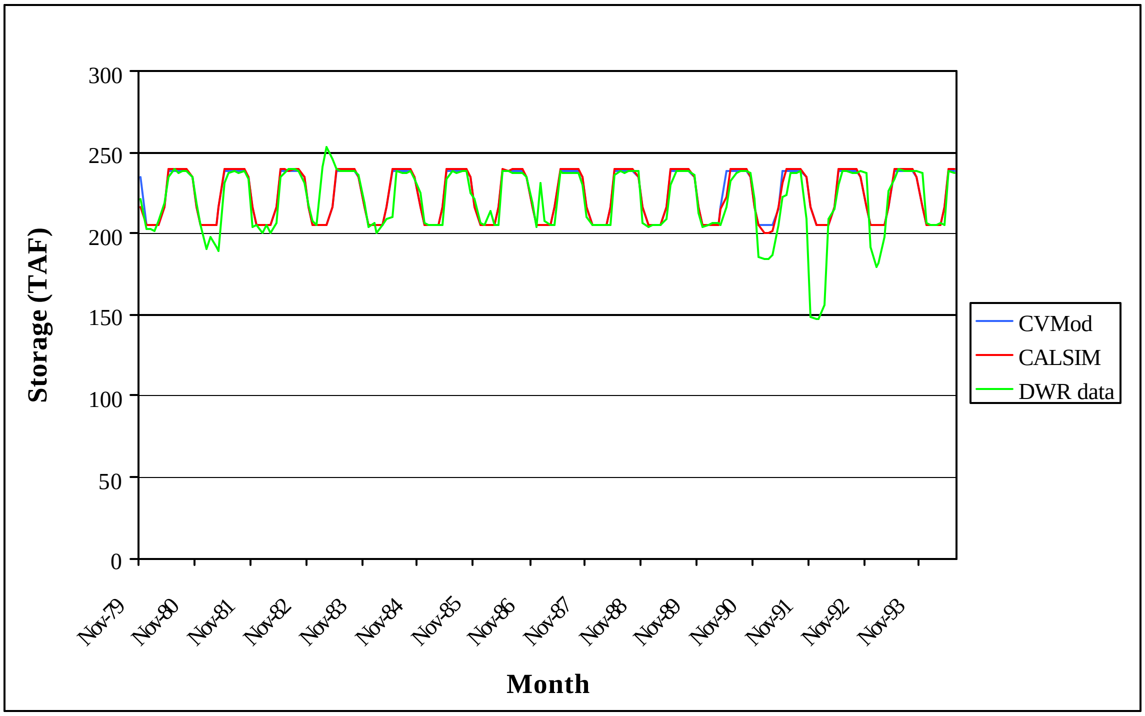
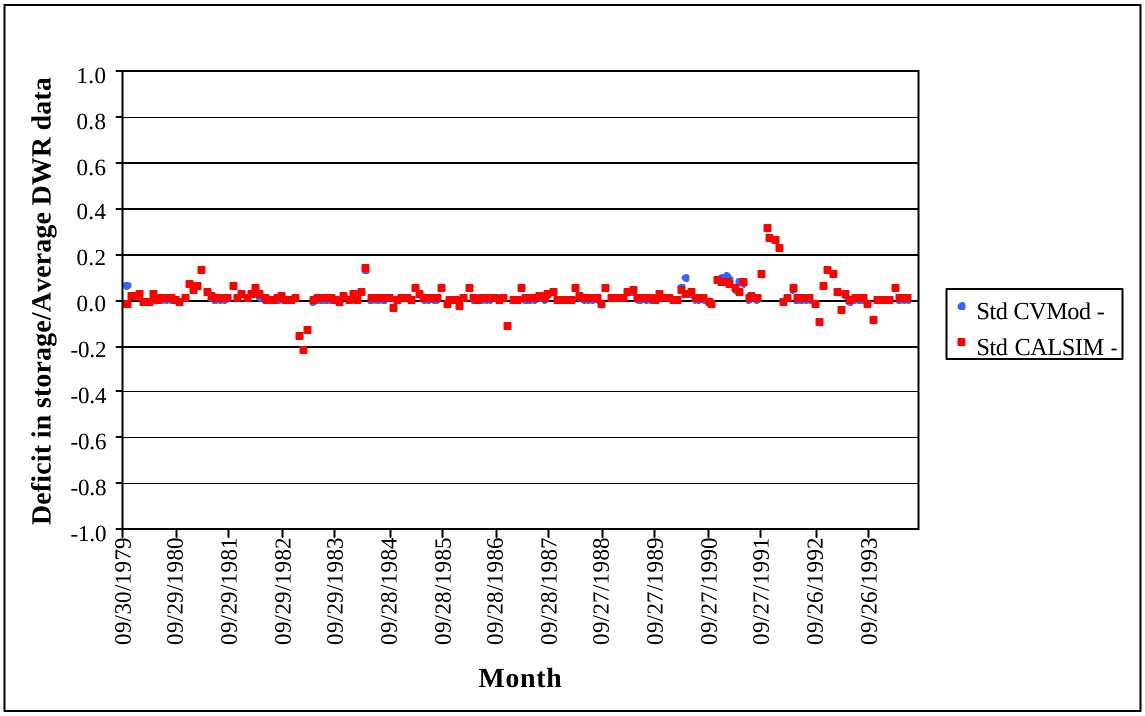


Figure A-3A-5. Comparison of end of month Whiskeytown storage levels



Standardized Deficit = (Model Result – DWR historic data) / Avera ge of DWR historic data

Figure A-3A-6. CALSIM-II and CVMod standardized deficit/surplus in Whiskeytown storage level compared to historic data

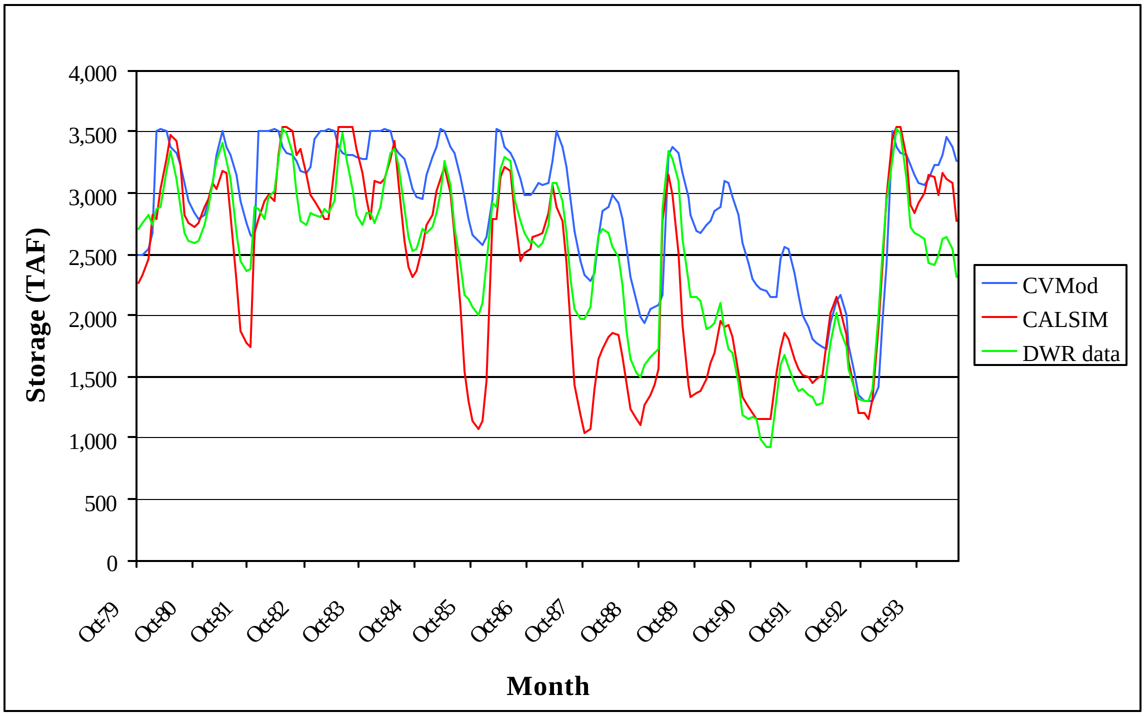
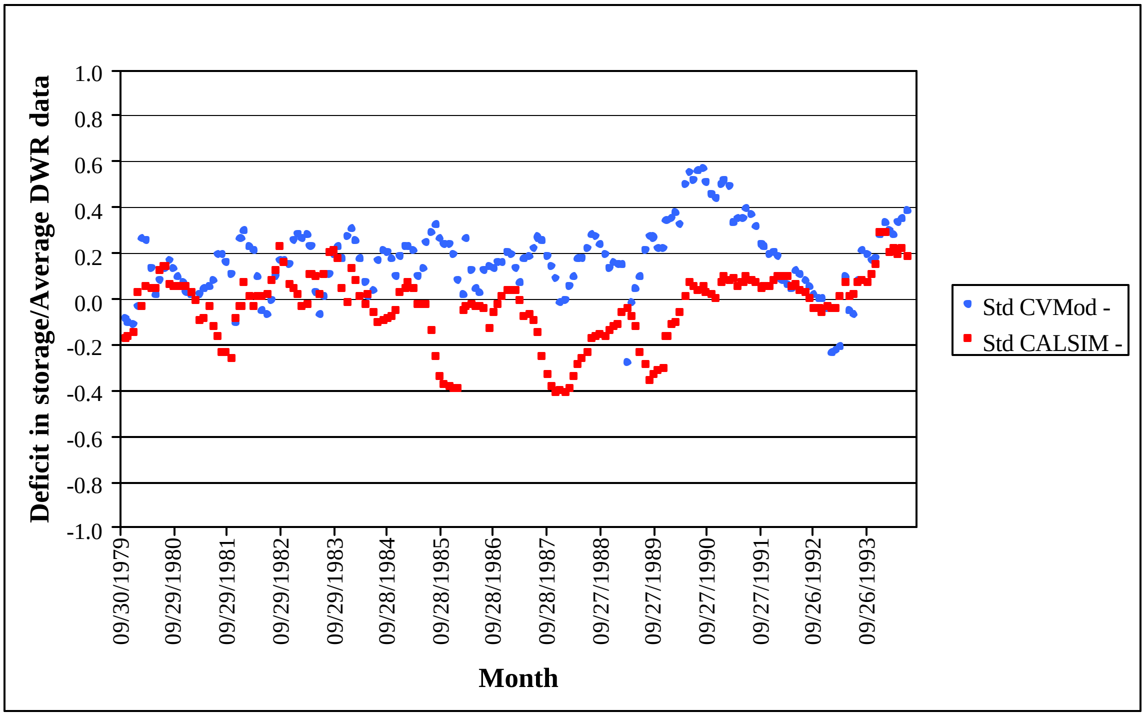


Figure A-3A-7. Comparison of end of month Oroville storage levels



Standardized Deficit = (Model Result – DWR historic data) / Average of DWR historic data

Figure A-3A-8. CALSIM-II and CVMod standardized deficit/surplus in Oroville storage level compared to historic data

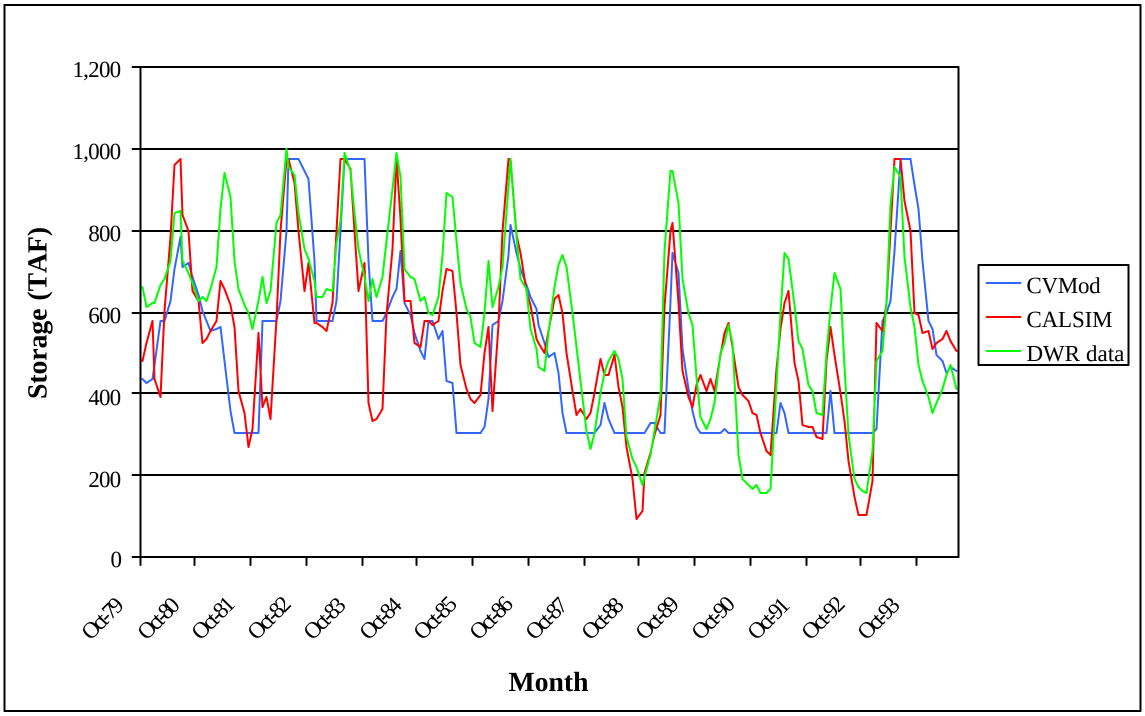
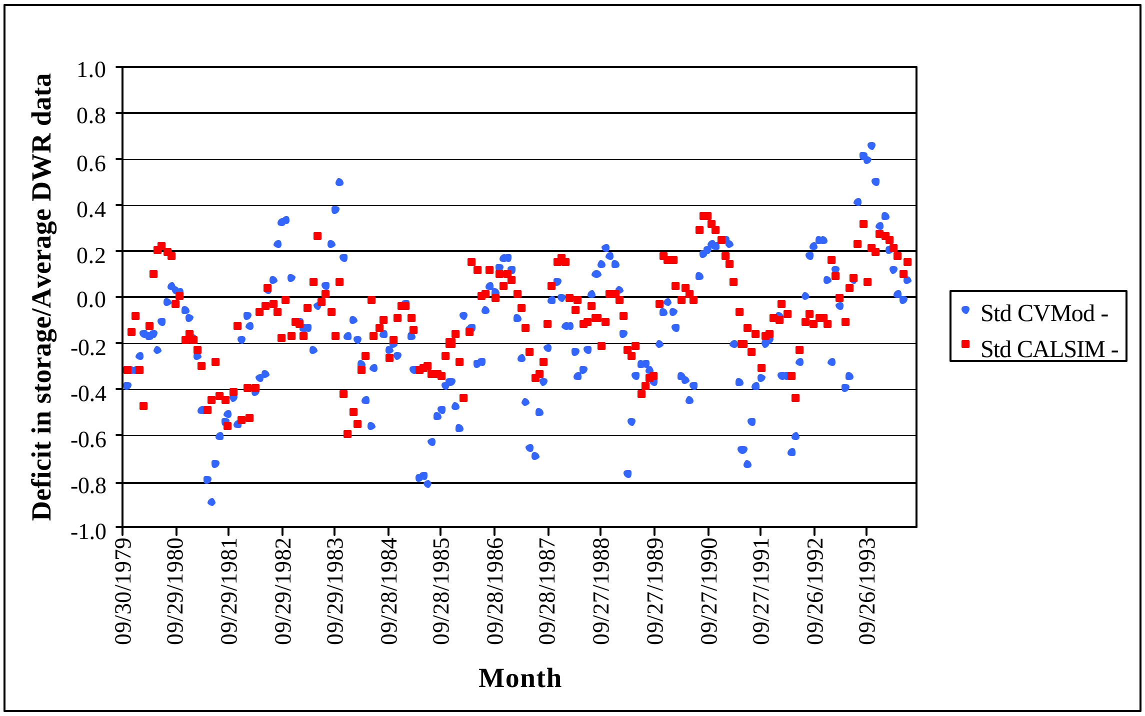


Figure A-3A-9. Comparison of end of month Folsom storage levels



Standardized Deficit = (Model Result – DWR historic data) / Average of DWR historic data

Figure A-3A-10. CALSIM-II and CVMod standardized deficit/surplus in Folsom storage level compared to historic data

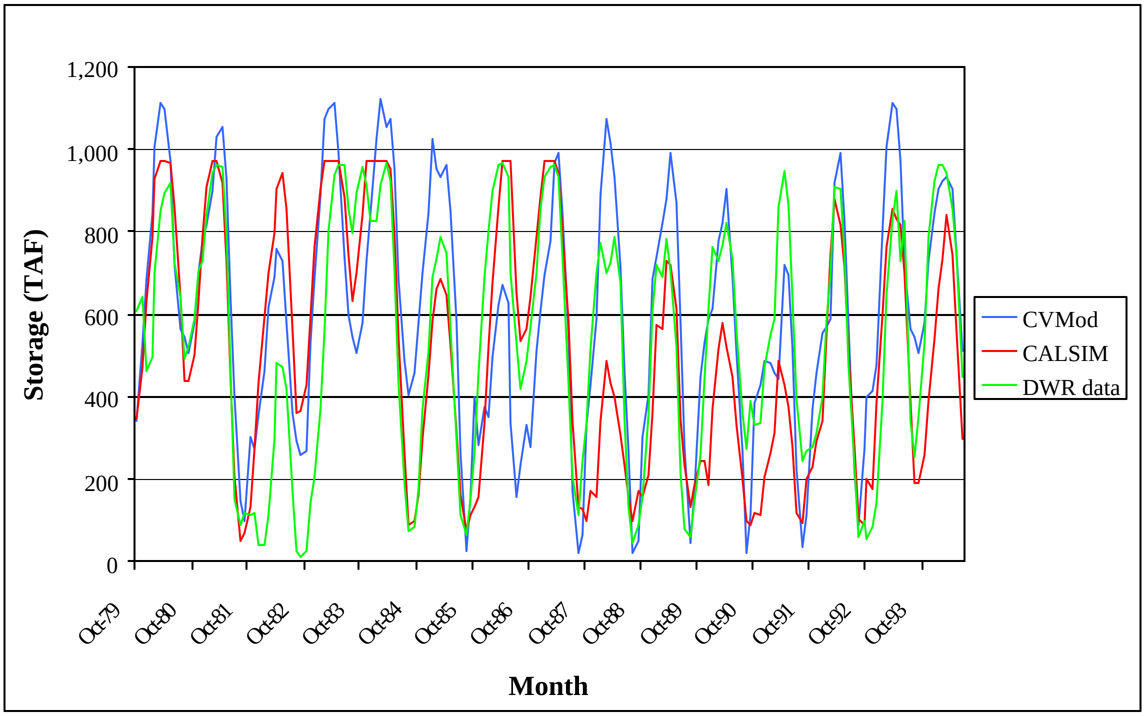
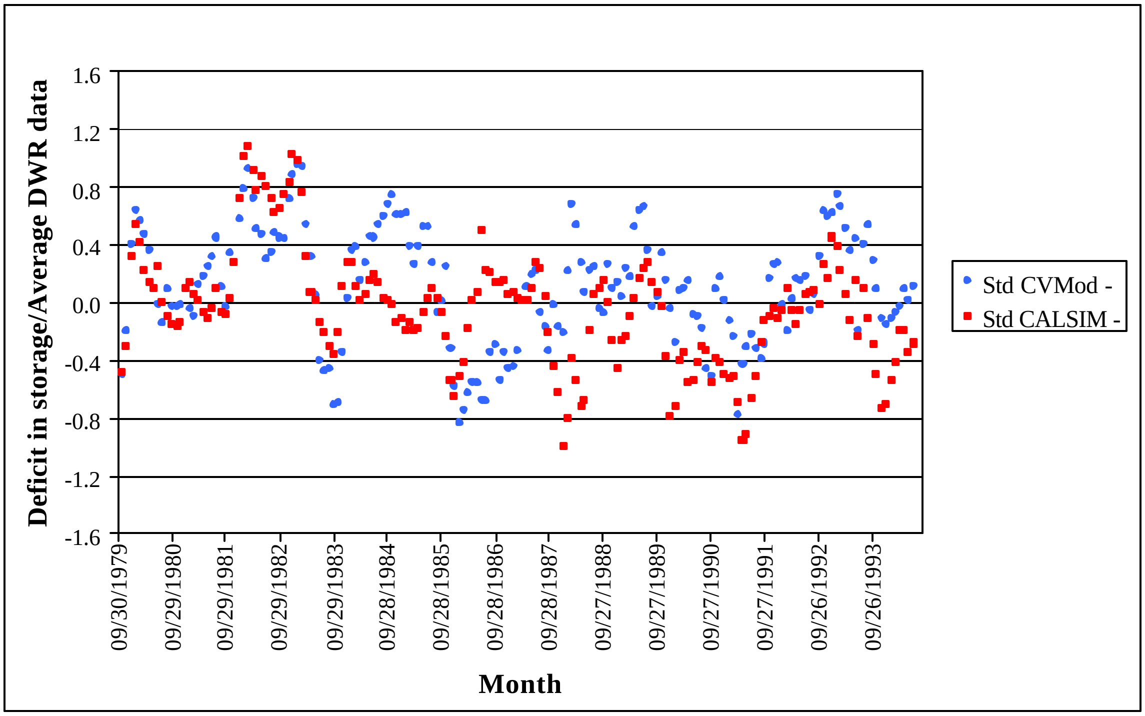


Figure A-3A-11. Comparison of end of month San Luis CVP storage levels



Standardized Deficit = (Model Result – DWR historic data) / Average of DWR historic data

Figure A-3A-12. CALSIM-II and CVMod standardized deficit/surplus in San Luis CVP storage level compared to historic data

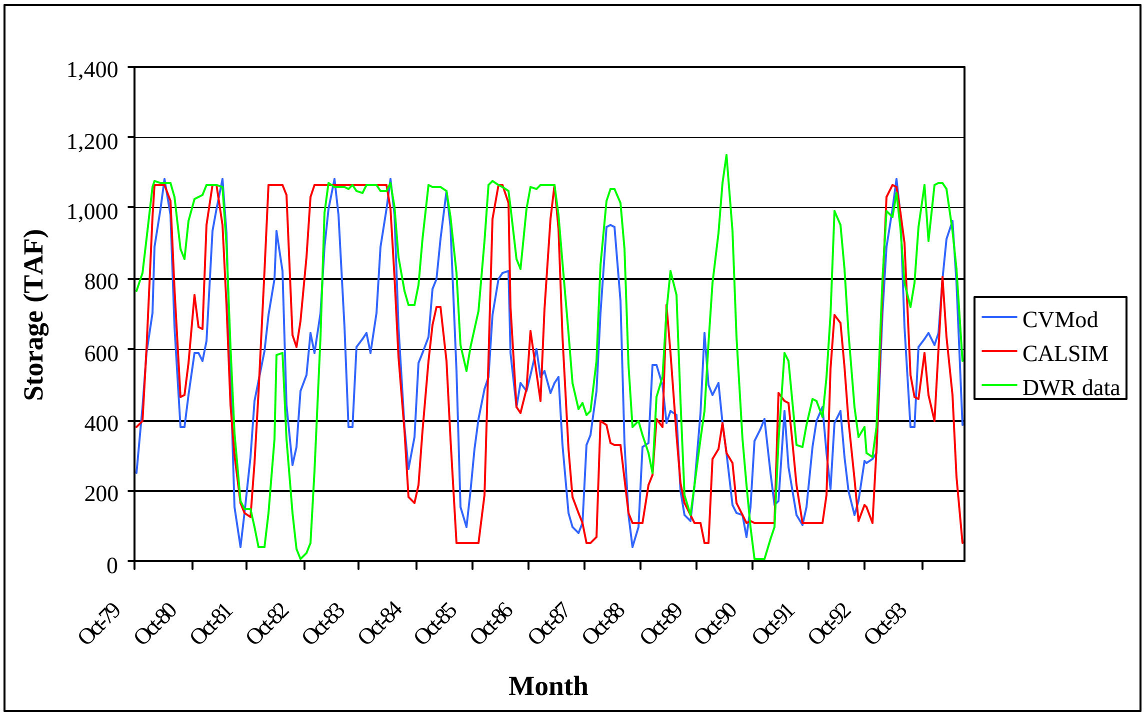
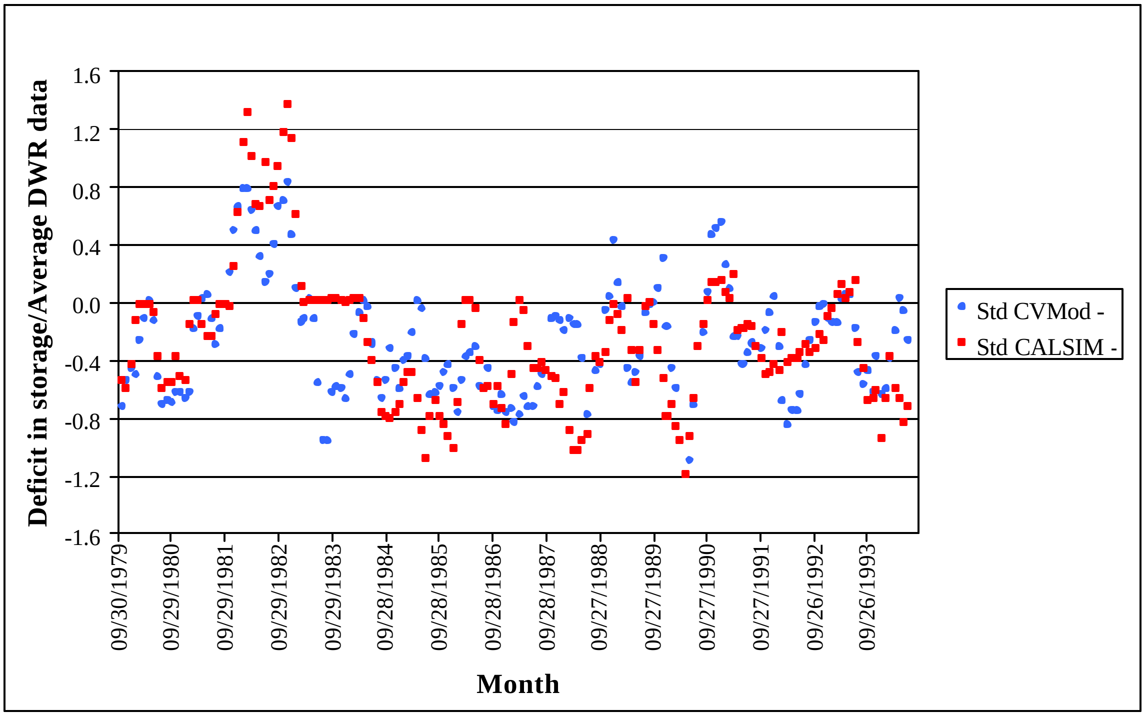


Figure A-3A-13. Comparison of end of month San Luis SWP storage levels



Standardized Deficit = (Model Result – DWR historic data) / Average of DWR historic data

Figure A-3A-14. CALSIM-II and CVMod standardized deficit/surplus in San Luis SWP storage level compared to historic data

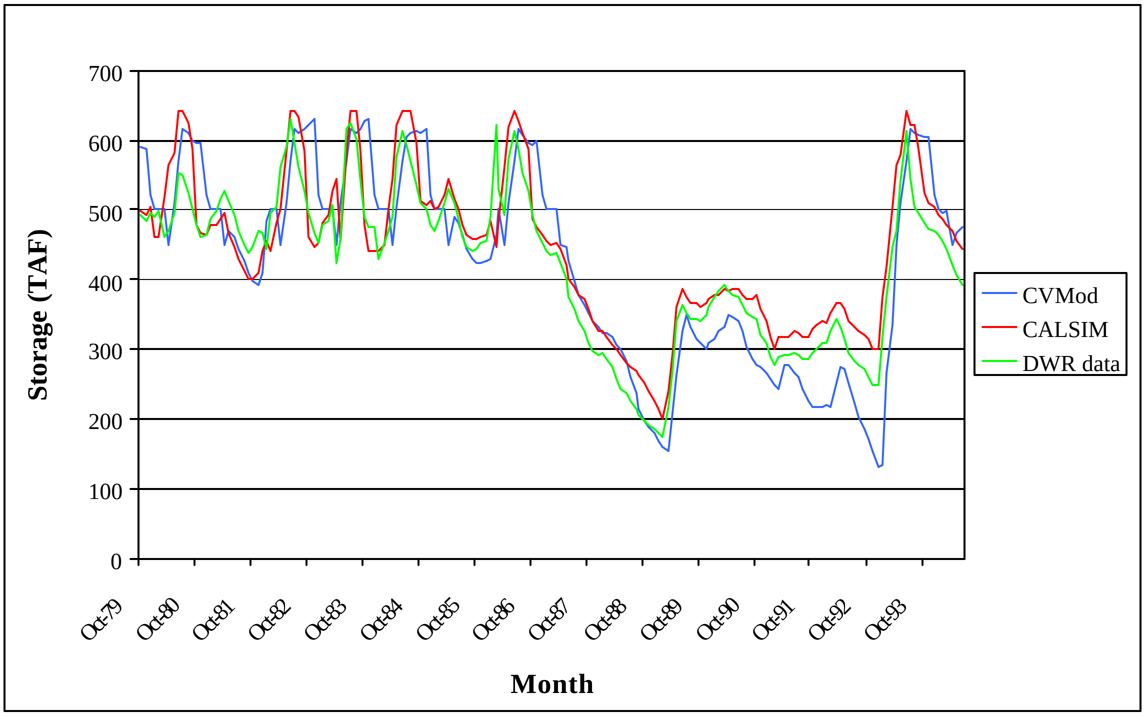
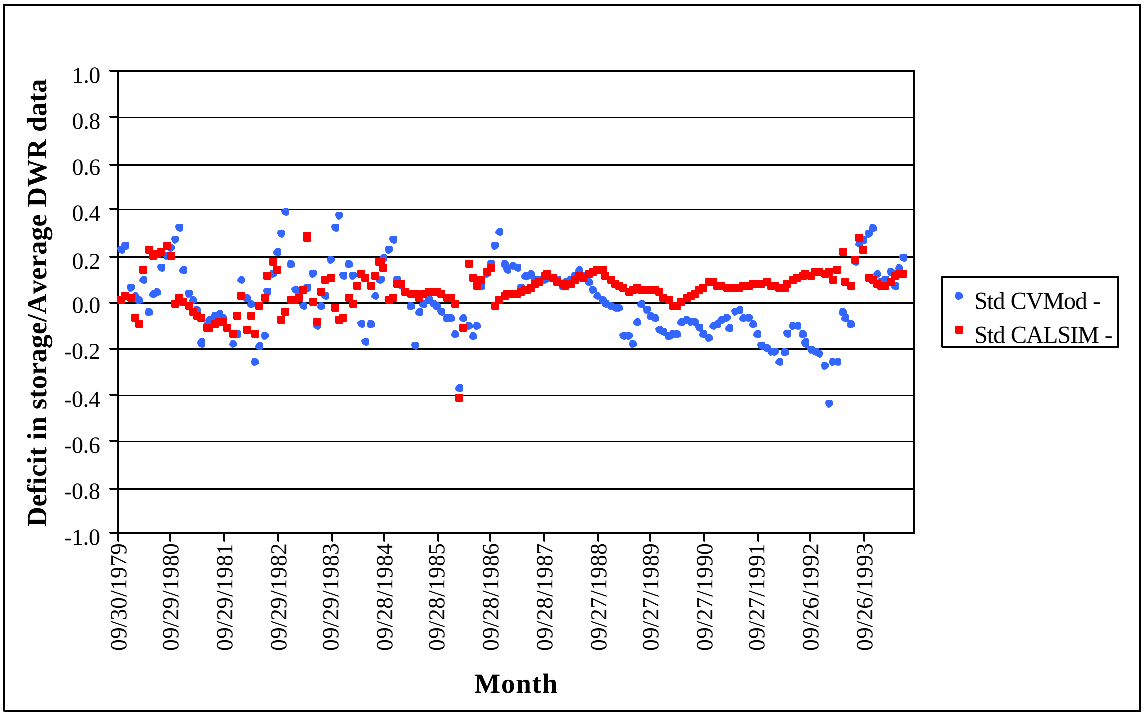


Figure A-3A-15. Comparison of end of month Camanche + Pardee storage levels



Standardized Deficit = (Model Result – DWR historic data) / Average of DWR historic data

Figure A-3A-16. CALSIM-II and CVMod standardized deficit/surplus in Camanche + Pardee storage level compared to historic data

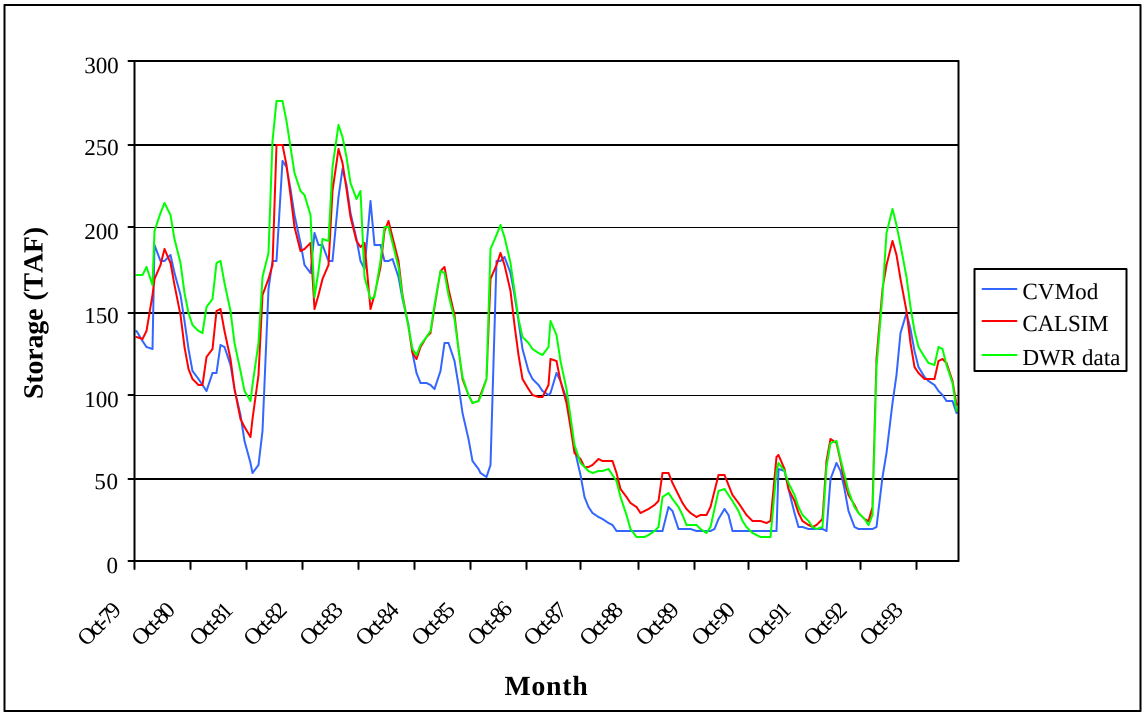
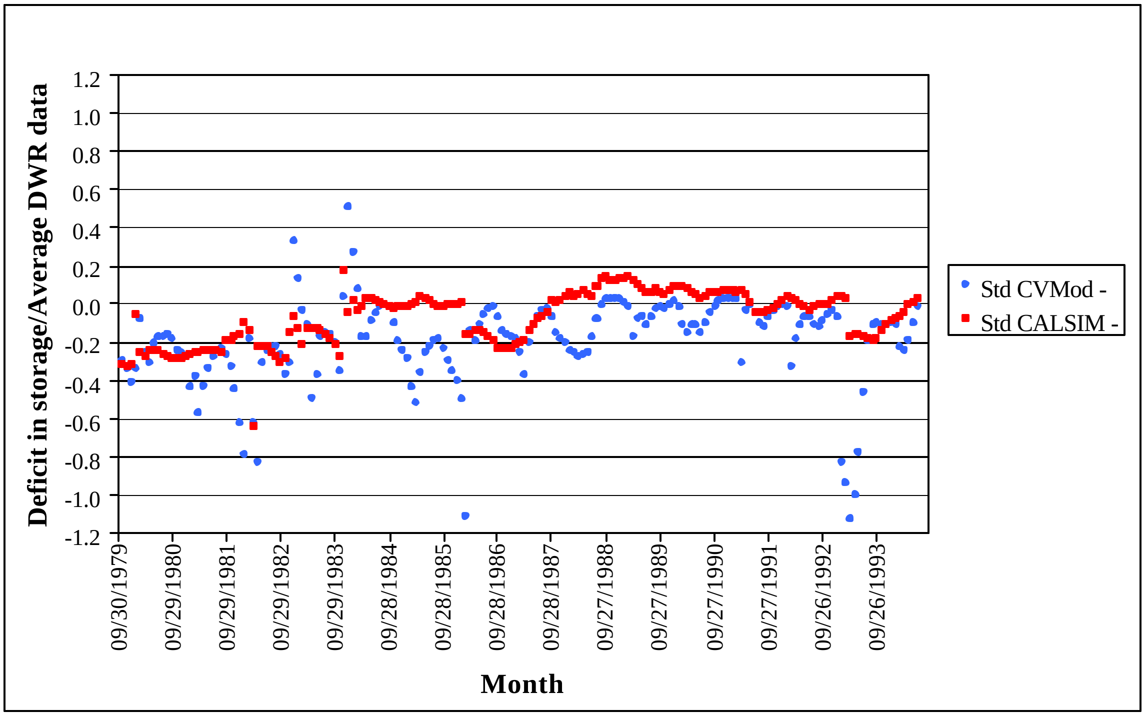


Figure A-3A-17. Comparison of end of month New Hogan storage levels



Standardized Deficit = (Model Result – DWR historic data) / Average of DWR historic data

Figure A-3A-18. CALSIM-II and CVMod standardized deficit/surplus in New Hogan storage level compared to historic data

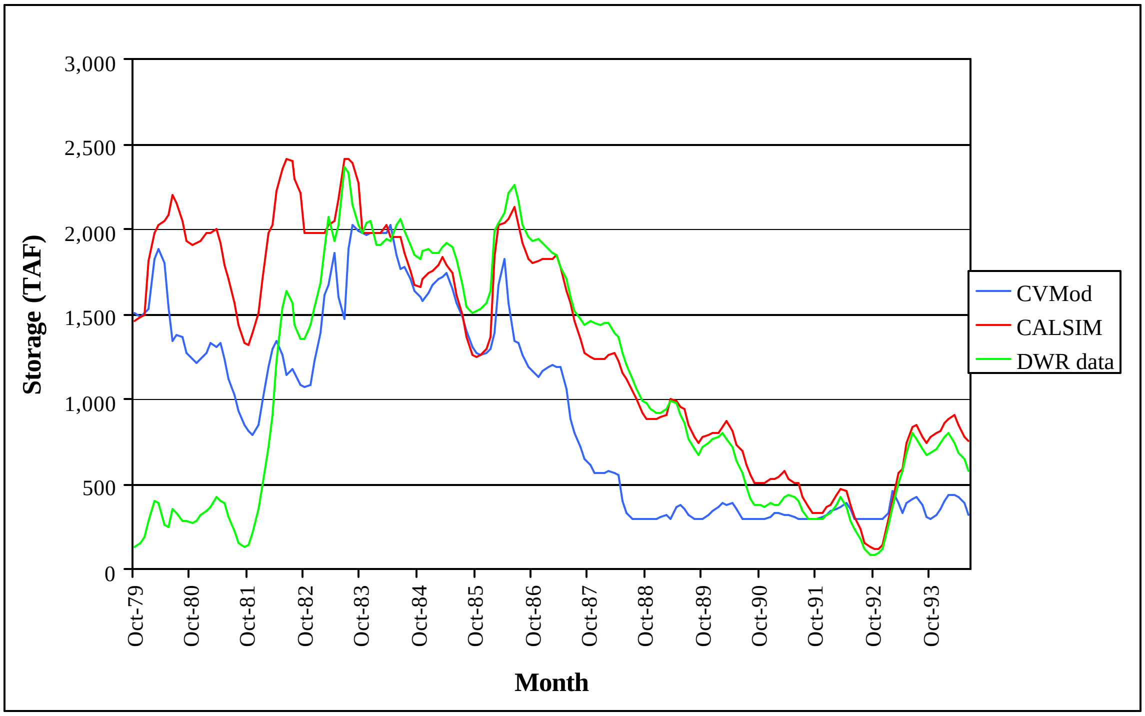
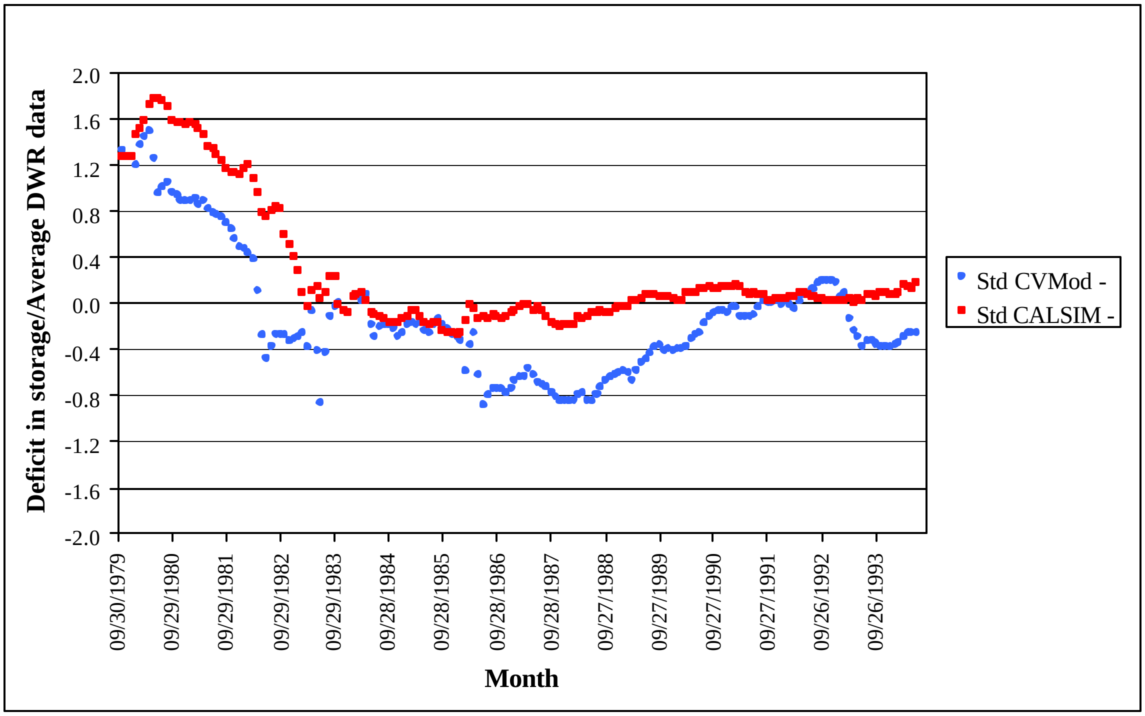


Figure A-3A-19. Comparison of end of month New Melones storage levels



Standardized Deficit = (Model Result – DWR historic data) / Average of DWR historic data

Figure A-3A-20. CALSIM-II and CVMod standardized deficit/surplus in New Melones storage level compared to historic data

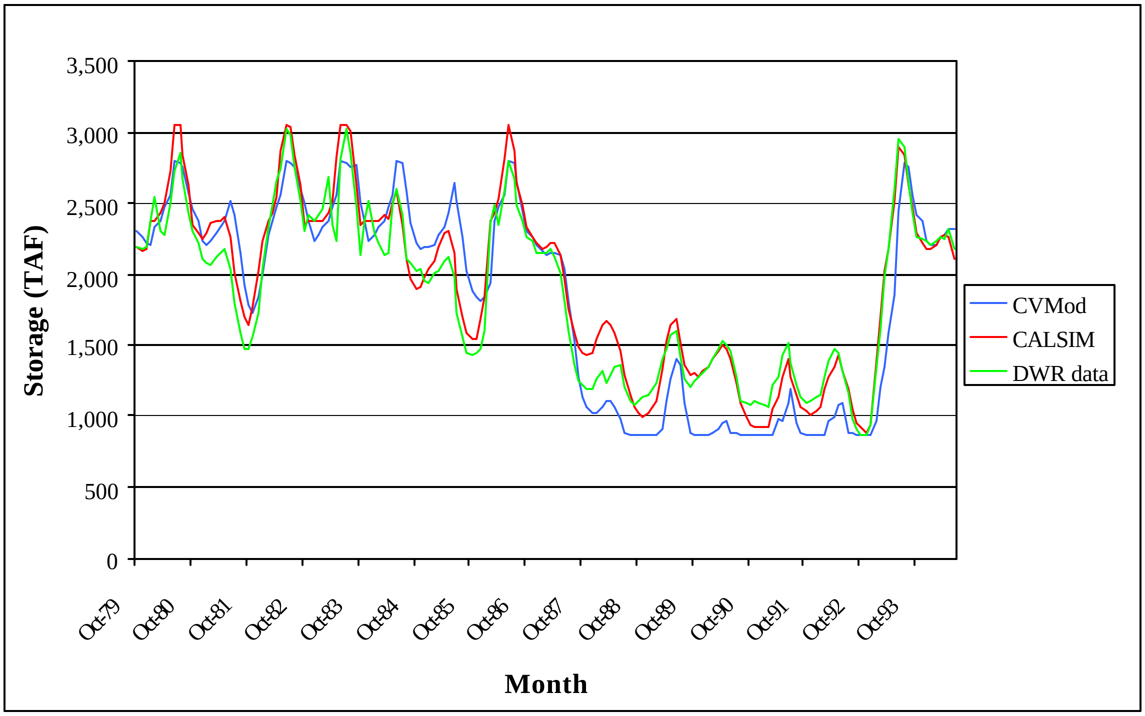
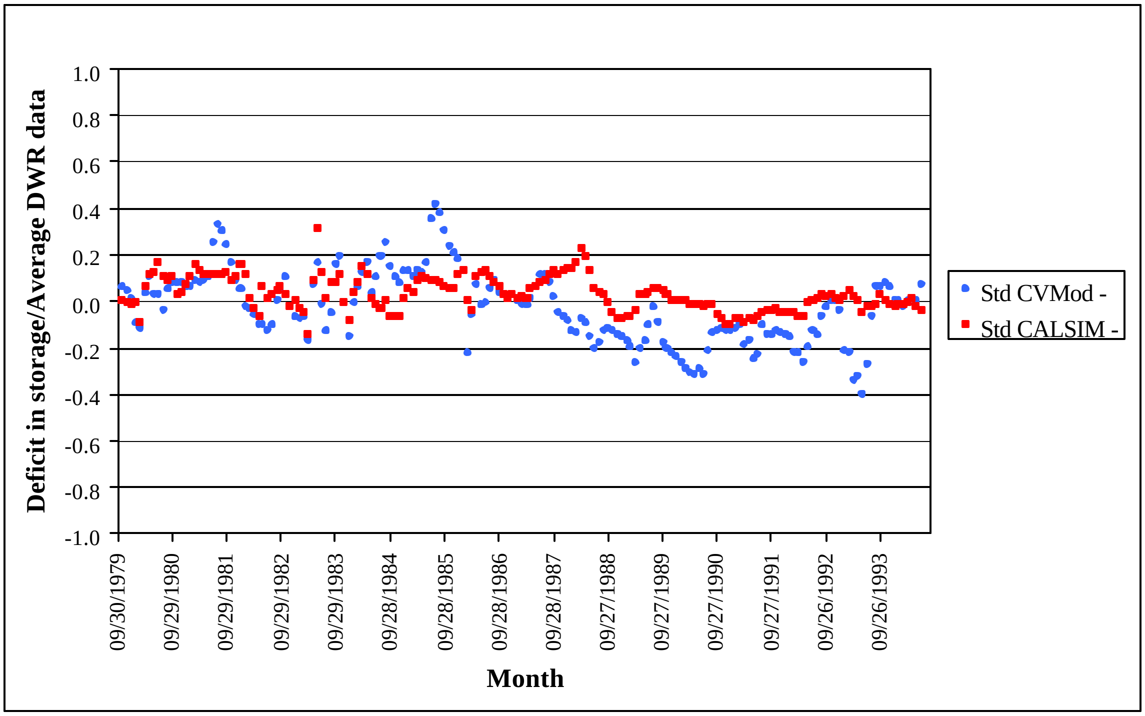


Figure A-3A-21. Comparison of end of month New Don Pedro + Lake McClure storage levels



Standardized Deficit = (Model Result – DWR historic data) / Average of DWR historic data

Figure A-3A-22. CALSIM-II and CVMod standardized deficit/surplus in New Don Pedro + Lake McClure storage level compared to historic data

Appendix D.4: Assessing California water system reliability using CALSIM-II model

This Appendix explains the sources of data and the procedure followed to estimate the reliability measures for different users in the California Central Valley using the results of the most recent available simulations runs for CALSIM-II, known as the Benchmark Studies (DWR/USBR, 2002). Using this available data on demands and deliveries (only surface water deliveries) we calculated monthly and annual quantity-based reliability measures (eq 1) defined as the percentage of water delivered compared to a target delivery level represented by the water demand[17]. With both the monthly and annually reliability measures we constructed frequency curves of these values and calculated an overall reliability measure (eq 2).

Monthly/Annually quantity-based reliability measure

$$R_{ij} = 1 - \frac{(Demand_{ij} - Delivery_{ij})}{Demand_{ij}} \text{ if } Demand_{ij} \geq Delivery_{ij}\text{; if not } R_{ij} = 1 \quad (1)$$

Overall reliability measure

$$R_i = \frac{\sum_j \left(Demand_{ij} - Delivery_{ij}\right)^+}{\sum_j Demand_{ij}} \quad (2)$$

where i represents a certain user (or group of users) and j represents the corresponding timestep (month or year). The + sign denotes that only positive values are considered.

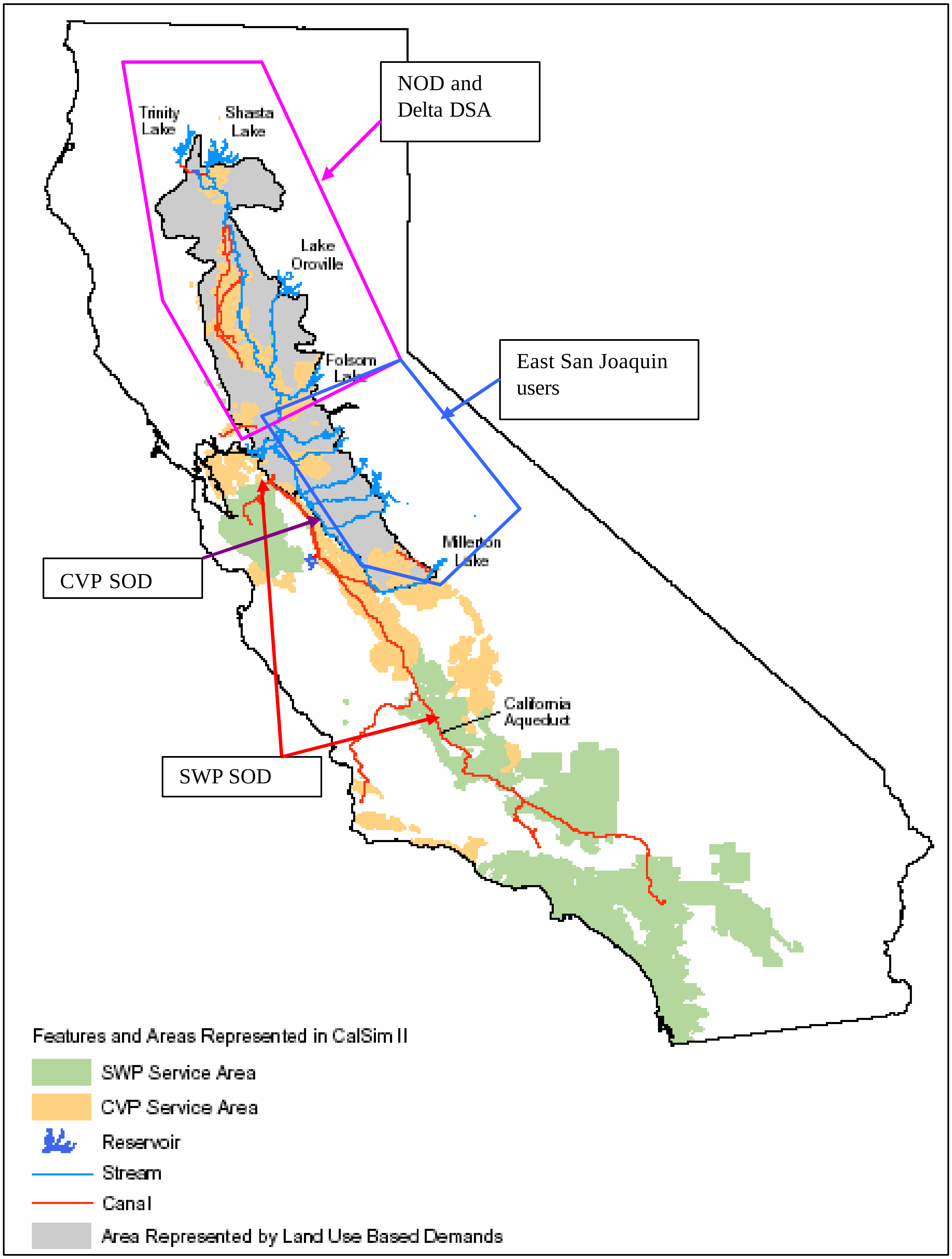
The analysis was done for different types of users according to their geographic location, their source of water and different water rights status. These different users were also aggregated into different levels. The first level considered the whole Central Valley system[18]. The second level compared reliability measures for broad geographic categories of users: North of the Delta (NOD) Project and non-project users; State Water Project (SWP) South of the Delta (SOD) users; Central Valley Project (CVP) SOD users and East San Joaquin users. Figures 6 shows a map of these broad categories of users. The third and final level went within some of these groups to asses the reliability for more specific type of users[19]. An example of the analysis done at this step was the comparison of the reliability among different types of CVP users SOD (i.e. Between Exchange, Agriculture, M&I and Refugee Contractors). Figure D.4-2 shows a schematic

[17] This definition is based on Hashimoto et al. (1982) and Bogardi J.J. and Verhoef A. (1995). A time-base definition of reliability would be the fraction of time a system is under a no failure mode defined by a certain target. Other measures of a system performance not included in this analysis are the vulnerability and resilience (see Hashimoto et al (1982).

[18] Only Delta users were not considered in the analysis because there are some concerns about the corresponding CALSIM-II results that need to be discussed with the DWR.

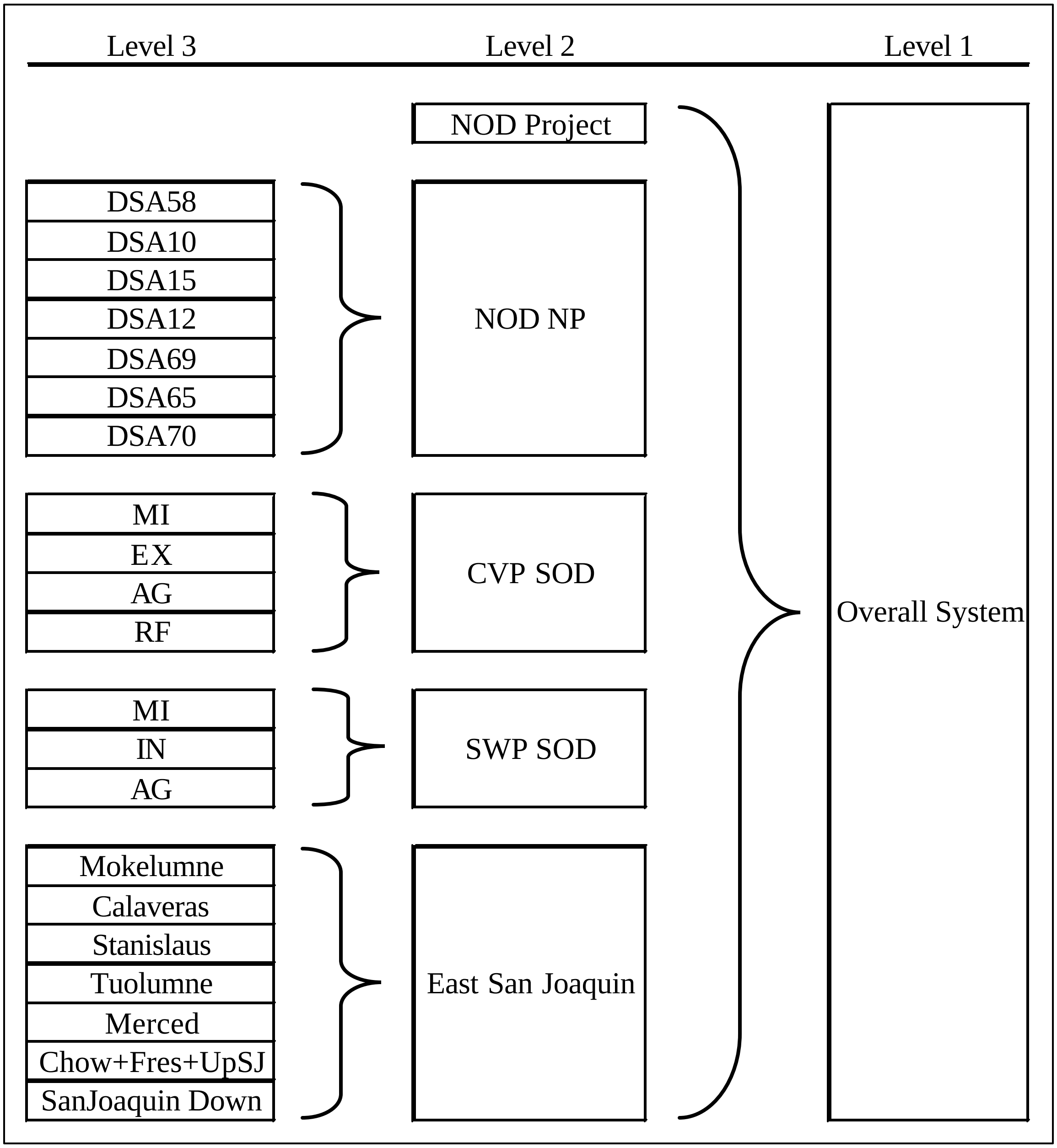
[19] Using CALSIM-II it's also possible to a further step analysis of the reliability at the ID district level but there's not a good representation of these users yet so we preferred not to do it at this time.

of how the different users in the Central Valley are classified into this different types and levels of aggregation.



Notes: NOD = North of the Delta; DSA = Depletion Study Areas;
CVP = Central Valley Project; SWP = State Water Project

Figure D.4-1. Geographic location of users within CALSIM-II



Notes: NOD = North of the Delta; SOD = South of the Delta; DSA = Depletion Study Areas; CVP = Central Valley Project; SWP = State Water Project; AG = Agriculture Contractor; SC = Settlement Contractor; MI = M&I contractor; RF = Refugee Contractor; EX = Exchange Contractor

Figure D.4-2. Schematic showing group of users within CALSIM-II

The following Tables detail the source of data from CALSIM-II runs that were used to estimate the reliability measures for all users included in Level 3 of aggregation. The aggregation of this data according to the schematic shown in Figure 2-1 was used to determine the reliability measure for users in Level 2 and 1. We didn't include arcs that represented only depletions with an associated accretion arc (there are many of these in the ESJ and Delta region). We also only include surface water deliveries.

Table D.4-1. CALSIM-II variables representing the demands and deliveries, for different water users in the Central Valley, used to estimate the reliability measures [(1)].

Level 2 **Level 3**	**Demand Arc**	**Delivery Arc [(2)]**
NOD NP [(3)]		
DSA 58 NP	0.1 * /DR58/DEMAND/	/D104_NP/FLOW-DELIVERY/
DSA 10 NP	0.81 * /DR10/DEMAND/	/D117A_NP/FLOW-DELIVERY/
DSA 12 NP	0.25 * /DR12/DEMAND/	/C144B_SPILL_NP/FLOW-CHANNEL/
DSA 15 NP	0.34 * /DR15/DEMAND/	/D128_NP/FLOW-DELIVERY/
DSA 69 NP	0.30 * /DR69/DEMAND/	/D211_NP/FLOW-DELIVERY/ /D213A_NP/FLOW-DELIVERY/ /D207A/FLOW-DELIVERY/ /D217/FLOW-DELIVERY/
DSA 65 NP	0.88 * /DR65/DEMAND/	/C152A_NP/FLOW-CHANNEL/
DSA 70 NP	0.62 * /DR70/DEMAND/	/D308_NP/FLOW-DELIVERY/ /D168/FLOW-DELIVERY/
NOD PRJ [(3)]		
DSA 58 PRJ	0.9 * /DR58/DEMAND/	/D104_PRJ/FLOW-DELIVERY/
DSA 10 PRJ	0.19 * /DR10/DEMAND/	/D112B_PRJ/FLOW-DELIVERY/ /D117A_PRJ/FLOW-DELIVERY/
DSA 12 PRJ	0.75 * /DR12/DEMAND/	/D122_PRJ/FLOW-DELIVERY/ /C144B_SPILL_PRJ/FLOW-CHANNEL/ /C142C/FLOW-CHANNEL/ /D112A_PRJ/FLOW-DELIVERY/
DSA 15 PRJ	0.66 * /DR15/DEMAND/	/D128_PRJ/FLOW-DELIVERY/
DSA 69 PRJ	0.70 * /DR69/DEMAND/	/D206A_PRJ/FLOW-DELIVERY/ /D206B_PRJ/FLOW-DELIVERY/ /D201_PRJ/FLOW-DELIVERY/ /D202_PRJ/FLOW-DELIVERY/ /D204_PRJ/FLOW-DELIVERY/ /D7A_PRJ/FLOW-DELIVERY/ /D7B_PRJ/FLOW-DELIVERY/ /D6_PRJ/FLOW-DELIVERY/

Level 2 Level 3	Demand Arc	Delivery Arc [2]
DSA 65 PRJ	0.12 * /DR65/DEMAND/	/C152A_PRJ/FLOW-CHANNEL/
DSA 70 PRJ	0.38 * /DR70/DEMAND/	/D304_OMI/FLOW-DELIVERY/ /D308_OMI/FLOW-DELIVERY/ /D309A_OMI/FLOW-DELIVERY/ /D308_PSC/FLOW-DELIVERY/
CVP SOD		
RF	/DEM_D708_PRF/DEMAND-CVP-RF/ /DEM_D856_PRF/DEMAND-CVP-RF/ /DEM_D607C_PRF/DEMAND-CVP-RF/	/D708_PRF/FLOW-DELIVERY/ /D856_PRF/FLOW-DELIVERY/ /D607C_PRF/FLOW-DELIVERY/
MI	/DEM_D711_PMI/DEMAND-CVP-MI/ /DEM_D844_PMI/DEMAND-CVP-MI/	/D711_PMI/FLOW-DELIVERY/ /D844_PMI/FLOW-DELIVERY/
EX	/DEM_D707_PEX/DEMAND-CVP-EX/ /DEM_D607B_PEX/DEMAND-CVP-EX/	/D707_PEX/FLOW-DELIVERY/ /D607B_PEX/FLOW-DELIVERY/
AG	/DEM_D700_PAG/DEMAND-CVP-AG/ /DEM_D701_PAG/DEMAND-CVP-AG/ /DEM_D710_PAG/DEMAND-CVP-AG/ /DEM_D706_PAG/DEMAND-CVP-AG/ /DEM_D833_PAG/DEMAND-CVP-AG/ /DEM_D835_PAG/DEMAND-CVP-AG/ /DEM_D837_PAG/DEMAND-CVP-AG/ /DEM_D839_PAG/DEMAND-CVP-AG/ /DEM_D841_PAG/DEMAND-CVP-AG/ /DEM_D843_PAG/DEMAND-CVP-AG/ /DEM_D855_PAG/DEMAND-CVP-AG/ /DEM_D607A_PAG/DEMAND-CVP-AG/	/D700_PAG/FLOW-DELIVERY/ /D701_PAG/FLOW-DELIVERY/ /D710_PAG/FLOW-DELIVERY/ /D706_PAG/FLOW-DELIVERY/ /D833_PAG/FLOW-DELIVERY/ /D835_PAG/FLOW-DELIVERY/ /D837_PAG/FLOW-DELIVERY/ /D839_PAG/FLOW-DELIVERY/ /D841_PAG/FLOW-DELIVERY/ /D843_PAG/FLOW-DELIVERY/ /D855_PAG/FLOW-DELIVERY/ /D607A_PAG/FLOW-DELIVERY/
SWP SOD		
MI	/DEM_D810_PMI/DEMAND-SWP-MI/ /DEM_D813_PMI/DEMAND-SWP-MI/ /DEM_D814_PMI/DEMAND-SWP-MI/ /DEM_D815_PMI/DEMAND-SWP-MI/ /DEM_D869_PMI/DEMAND-SWP-MI/ /DEM_D851_PMI/DEMAND-SWP-MI/ /DEM_D877_PMI/DEMAND-SWP-MI/ /DEM_D878_PMI/DEMAND-SWP-MI/ /DEM_D879_PMI/DEMAND-SWP-MI/ /DEM_D881_PMI/DEMAND-SWP-MI/ /DEM_D25_PMI/DEMAND-SWP-MI/ /DEM_D883_PMI/DEMAND-SWP-MI/ /DEM_D884_PMI/DEMAND-SWP-MI/ /DEM_D27_PMI/DEMAND-SWP-MI/ /DEM_D885_PMI/DEMAND-SWP-MI/ /DEM_D899_PMI/DEMAND-SWP-MI/ /DEM_D895_PMI/DEMAND-SWP-MI/	/D810_PMI/FLOW-DELIVERY/ /D813_PMI/FLOW-DELIVERY/ /D814_PMI/FLOW-DELIVERY/ /D815_PMI/FLOW-DELIVERY/ /D869_PMI/FLOW-DELIVERY/ /D851_PMI/FLOW-DELIVERY/ /D877_PMI/FLOW-DELIVERY/ /D878_PMI/FLOW-DELIVERY/ /D879_PMI/FLOW-DELIVERY/ /D881_PMI/FLOW-DELIVERY/ /D25_PMI/FLOW-DELIVERY/ /D883_PMI/FLOW-DELIVERY/ /D884_PMI/FLOW-DELIVERY/ /D27_PMI/FLOW-DELIVERY/ /D885_PMI/FLOW-DELIVERY/ /D899_PMI/FLOW-DELIVERY/ /D895_PMI/FLOW-DELIVERY/

Level 2 Level 3	Demand Arc	Delivery Arc (2)
	/DEM_D886_PMI/DEMAND-SWP-MI/	/D886_PMI/FLOW-DELIVERY/
	/DEM_D887_PMI/DEMAND-SWP-MI/	/D887_PMI/FLOW-DELIVERY/
	/DEM_D888_PMI/DEMAND-SWP-MI/	/D888_PMI/FLOW-DELIVERY/
	/DEM_D28_PMI/DEMAND-SWP-MI/	/D28_PMI/FLOW-DELIVERY/
	/DEM_D29_PMI/DEMAND-SWP-MI/	/D29_PMI/FLOW-DELIVERY/
	/DEM_D896_PMI/DEMAND-SWP-MI/	/D896_PMI/FLOW-DELIVERY/
IN	/DEM_D810_PIN/DEMAND-SWP-IN/	/D810_PIN/FLOW-DELIVERY/
	/DEM_D814_PIN/DEMAND-SWP-IN/	/D814_PIN/FLOW-DELIVERY/
	/DEM_D815_PIN/DEMAND-SWP-IN/	/D815_PIN/FLOW-DELIVERY/
	/DEM_D868_PIN/DEMAND-SWP-IN/	/D868_PIN/FLOW-DELIVERY/
	/DEM_D846_PIN/DEMAND-SWP-IN/	/D846_PIN/FLOW-DELIVERY/
	/DEM_D848_PIN/DEMAND-SWP-IN/	/D848_PIN/FLOW-DELIVERY/
	/DEM_D849_PIN/DEMAND-SWP-IN/	/D849_PIN/FLOW-DELIVERY/
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	/DEM_D899_PIN/DEMAND-SWP-IN/	/D899_PIN/FLOW-DELIVERY/
	/DEM_D895_PIN/DEMAND-SWP-IN/	/D895_PIN/FLOW-DELIVERY/
AG	/DEM_D867_PAG/DEMAND-SWP-AG/	/D867_PAG/FLOW-DELIVERY/
	/DEM_D868_PAG/DEMAND-SWP-AG/	/D868_PAG/FLOW-DELIVERY/
	/DEM_D802_PAG/DEMAND-SWP-AG/	/D802_PAG/FLOW-DELIVERY/
	/DEM_D846_PAG/DEMAND-SWP-AG/	/D846_PAG/FLOW-DELIVERY/
	/DEM_D847_PAG/DEMAND-SWP-AG/	/D847_PAG/FLOW-DELIVERY/
	/DEM_D848_PAG/DEMAND-SWP-AG/	/D848_PAG/FLOW-DELIVERY/
	/DEM_D849_PAG/DEMAND-SWP-AG/	/D849_PAG/FLOW-DELIVERY/
	/DEM_D851_PAG/DEMAND-SWP-AG/	/D851_PAG/FLOW-DELIVERY/
	/DEM_D853_PAG/DEMAND-SWP-AG/	/D853_PAG/FLOW-DELIVERY/
	/DEM_D859_PAG/DEMAND-SWP-AG/	/D859_PAG/FLOW-DELIVERY/
	/DEM_D863_PAG/DEMAND-SWP-AG/	/D863_PAG/FLOW-DELIVERY/
ESJ		
Mokelumne	/DEMAND_D90_PAG/DEMAND/	/D90_PAG/FLOW-DELIVERY/
	/DEMAND_D90_PMI/DEMAND/	/D90_PMI/FLOW-DELIVERY/
	/DEMAND_D502_PAG/DEMAND/	/D502_PAG/FLOW-DELIVERY/
	/DEMAND_D502_PMI/DEMAND/	/D502_PMI/FLOW-DELIVERY/
	/DEMAND_D503A_NP/DEMAND/	/D503A_NP/FLOW-DELIVERY/
	/DEMAND_D503A_PAG/DEMAND/	/D503A_PAG/FLOW-DELIVERY/
	/DEMAND_D503A_PMI/DEMAND/	/D503A_PMI/FLOW-DELIVERY/
Calaveras	/DEMAND_D506_PAG/DEMAND/	/D506_PAG_SW/FLOW-DELIVERY/
	/DEMAND_D506_PMI/DEMAND/	/D506_PMI_SW/FLOW-DELIVERY/
	/DEMAND_D507A_NP/DEMAND/	/D507A_NP_SW/FLOW-DELIVERY/
	/DEMAND_D507A_PAG/DEMAND/	/D507A_PAG_SW/FLOW-DELIVERY/
	/DEMAND_D507A_PMI/DEMAND/	/D507A_PMI_SW/FLOW-DELIVERY/

Level 2 Level 3	Demand Arc	Delivery Arc (2)
Stanislaus	demand_D520_PAG (4) demand_D520_PMI (4) demand_D16A_OID (4) demand_D16A_SSJID (4) /DEMAND_D525/DEMAND/	/D520_CSJSEWD_PAG/FLOW-DELIVERY/ /D520_SEWD_PMI/FLOW-DELIVERY/ /D16A_OID/FLOW-DELIVERY/ /D16A_SSJID/FLOW-DELIVERY/ /D525_NP/FLOW-DELIVERY/
Tuolumne	/DEMAND_D540_PAG/DEMAND/ /DEMAND_D540_PMI/DEMAND/ /DEMAND_D541_PAG/DEMAND/ /DEMAND_D541_PMI/DEMAND/ /DEMAND_D544/DEMAND/	/D540_PAG_SW/FLOW-DELIVERY/ /D540_PMI_SW/FLOW-DELIVERY/ /D541_PAG_SW/FLOW-DELIVERY/ /D541_PMI_SW/FLOW-DELIVERY/ /D544_NP/FLOW-DELIVERY/
Merced	/DEMAND_D562_PAG/DEMAND/ /DEMAND_D562_PMI/DEMAND/ /DEMAND_D567/DEMAND/	/D562_PAG_SW/FLOW-DELIVERY/ /D562_PMI_SW/FLOW-DELIVERY/ /D567_NPSW/FLOW-DELIVERY/
Chowchilla +Fresno + Upper San J.	/DEMAND_D580_PAG/DEMAND/ /DEMAND_D580_PMI/DEMAND/ /DEMAND_D583_PAG/DEMAND/ /DEMAND_D583_PMI/DEMAND/ /DEMAND_D600A/DEMAND/ /DEMAND_D602/DEMAND/	/D580_PAG_SW/FLOW-DELIVERY/ /D580_PMI_SW/FLOW-DELIVERY/ /D583_PAG_SW/FLOW-DELIVERY/ /D583_PMI_SW/FLOW-DELIVERY/ /D600A/FLOW-DELIVERY/ /D602_NP/FLOW-DELIVERY/
SanJoaquin Down	/DEMAND_D613/DEMAND/ /DEMAND_D621B/DEMAND/ /DEMAND_D625/DEMAND/ /DEMAND_D639/DEMAND/	/D613_NP/FLOW-DELIVERY/ /D621B_NP/FLOW-DELIVERY/ /D625_NP/FLOW-DELIVERY/ /D639_NP/FLOW-DELIVERY/

Notes:

(1) All these variable names represent the "B" and "C" parts of DSS-type of time-series of data available from CALSIM-II Benchmark studies run (http://modeling.water.ca.gov/hydro/studies/Version2_Benchmark.html).
Demand DSS files are found in:
\BST_2001D10A_ANNBENCHMARK_1_2\common\DSS\2001D10ASV.DSS
Deliveries DSS files are found in:
\BST_2001D10A_ANNBENCHMARK_1_2\D1641\DSS\2001D10ADV.DSS
We're not considering users represented just by a depletion arc coupled with an accretion arc. These are common in the Delta and East San Joaquin regions.

(2) We're only considering surface water deliveries and not groundwater pumping which fulfill part of the user's demands.

(3) Demands for NOD users within CALSIM-II are timeseries of land-use based estimates of demands (e.g. dr10) that are further split into project and non-project demands based on predefined percentages.

(4) These demands are considered in CALSIM-II as intermediate variables not included in the final output. What I've considered here is the name of these intermediate variables (see CALSIM file: *stan_dem.wresl*).

IIIB. Accuracy of DWR Water Flow Forecasts

The forecasts of water flows and streamflows published by DWR at the beginning of each year are likely to be a crucial input to water district managers' expectations regarding their warm-season water supplies. However, since these are only forecasts, they are likely to contain some degree of error. The purpose of this research is to measure the error bands that might be placed around the DWR forecasts.

Preliminary analyses of the DWR water flow forecasts have been performed on six California rivers for the period 1998-2003. Four rivers, the Mokelumne, Feather Yuba and American Rivers, drain medium-elevation watersheds (with an average elevation below 1,600 feet). Two rivers, the Kings and the San Joaquin Rivers, drain high-elevation watersheds (with an average elevation above 1,600).

These forecasts have been assembled for different months or dates and graphed as a percent of actual flow. ("Actual" flow in this case is a reconstructed natural flow: the sum of real flow and upstream diversions.) For each river, percent difference between 10%, 50%, and 90% exceedence forecasts and actual flows were graphed vs. forecasts date (Figures 1-6). The 10% exceedence forecast is interpreted as an upper bound forecast; with a 10% chance that actual flows will exceed the indicated level. The 90% exceedence forecast is interpreted as a lower bound forecast, with a 90 % chance that actual flows will exceed the indicated level. The 90% and 10% exceedence forecasts bracket the most likely 50% exceedence forecast.

The accuracy of the forecasts is indicated by the vertical width of the spread between the 10% and 90% exceedence forecasts provided at different points in time. As expected, forecast accuracy improves over time (moving from left to right), as the period between the forecast date and delivery shortens. There is a relatively wide spread in the January and February forecasts and almost no spread in the June and July forecasts. More interesting, forecast accuracy also seems to improve with watershed elevation; higher watersheds tend to have more accurate forecasts than lower watersheds. To see this, compare the January forecast spread in the low elevation watersheds (Figures 1-4) and the high elevation watersheds (Figures 5-6). This correlation may be related to the dominance of snowmelt in the annual hydrograph of higher watersheds. If so, reduction of the snowpack due to climate change can have a substantial impact on future forecast reliability.

The largest correlation between forecast accuracy and a natural factor is apparent when considering only particularly wet and dry seasons (Figures 7-8). As expected, flow forecasts tend to be low for wet years. Error is almost entirely in the range of –50% to 0. In contrast, errors for dry years regularly ranges up to +200%. This correlation may also be due to the dominance and predictability of snowmelt during wetter years.

Interestingly, errors tend to converge to zero in a linear fashion when considering either wet or dry years, compared to the curved convergences seen in the river-based analysis.

Details of interest for future study:

- Forecasts for higher elevation watersheds appear to have more accurate forecasts in general.
- Forecasts in wetter years appear to have more accurate forecasts in general.
- The range of forecasts for higher elevation watersheds is smaller than for lower elevation.
- Forecasts for higher elevation watersheds appear to converge faster and more uniformly to actual flows than those for lower elevations.
- The 50% exceedance forecasts tend to slightly underestimate actual flows for higher elevation watersheds, and more significantly overestimate flows for lower elevation watersheds.
- Forecast errors tend to converge linearly in analysis of wet and dry years, while per-river analysis yields curved error converges.

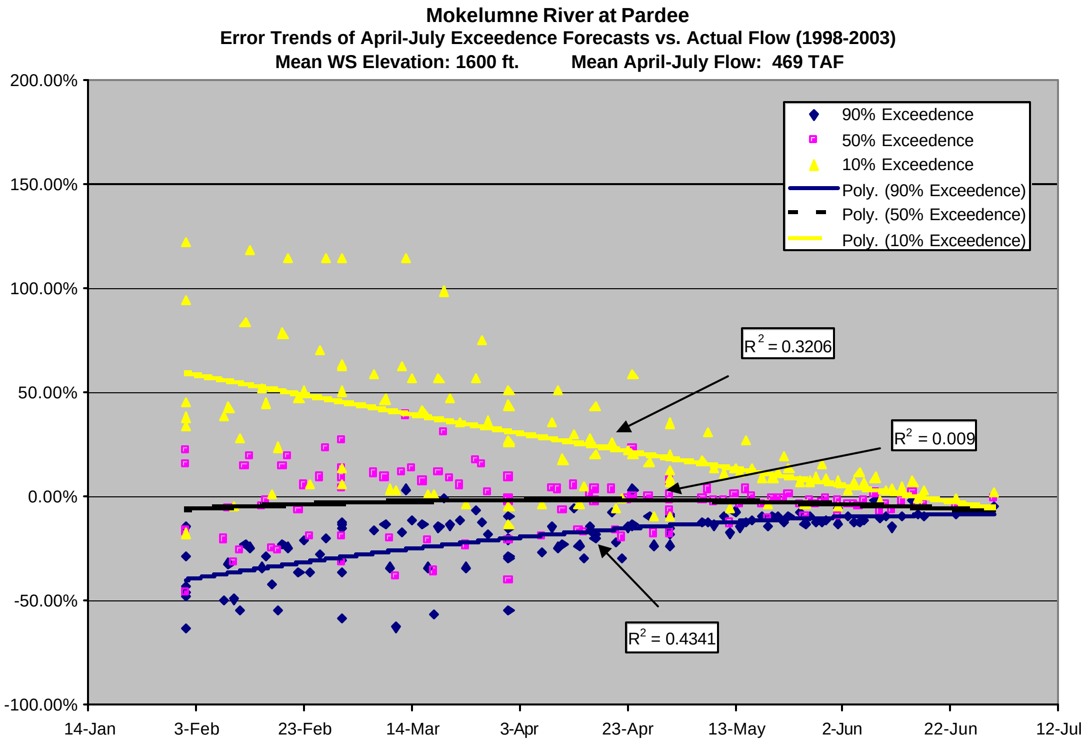

Figure 3B-1. Mokelumne River Forecast Analysis

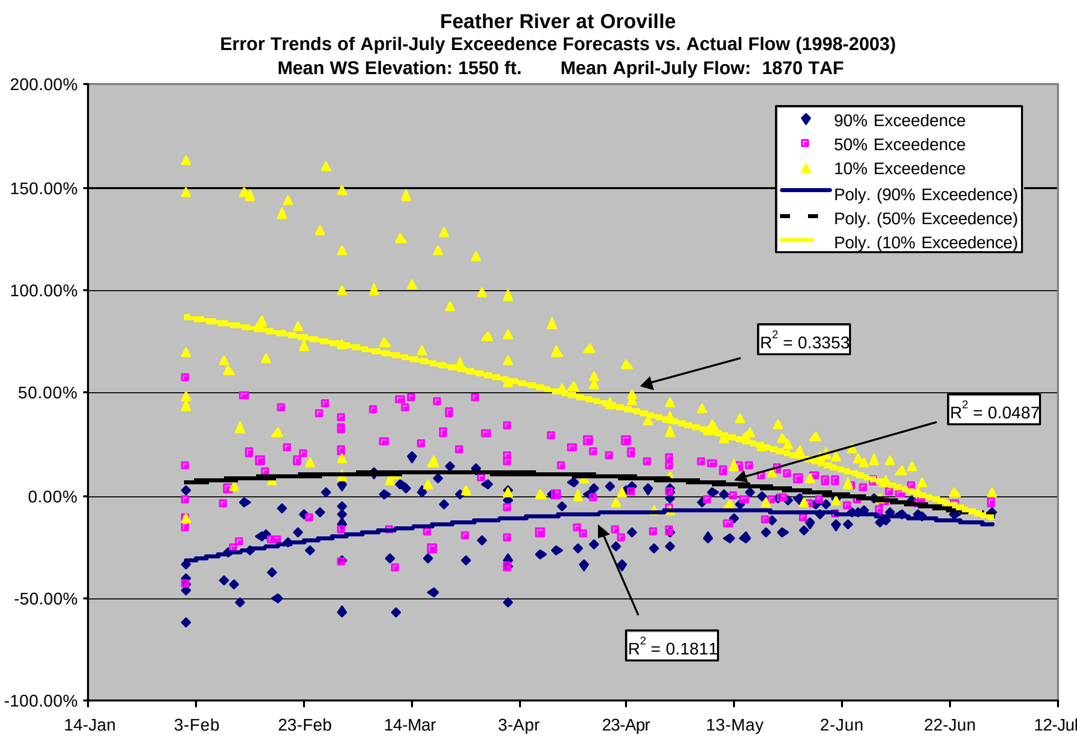

Figure 3B-2. Feather River Flow Forecast Analysis

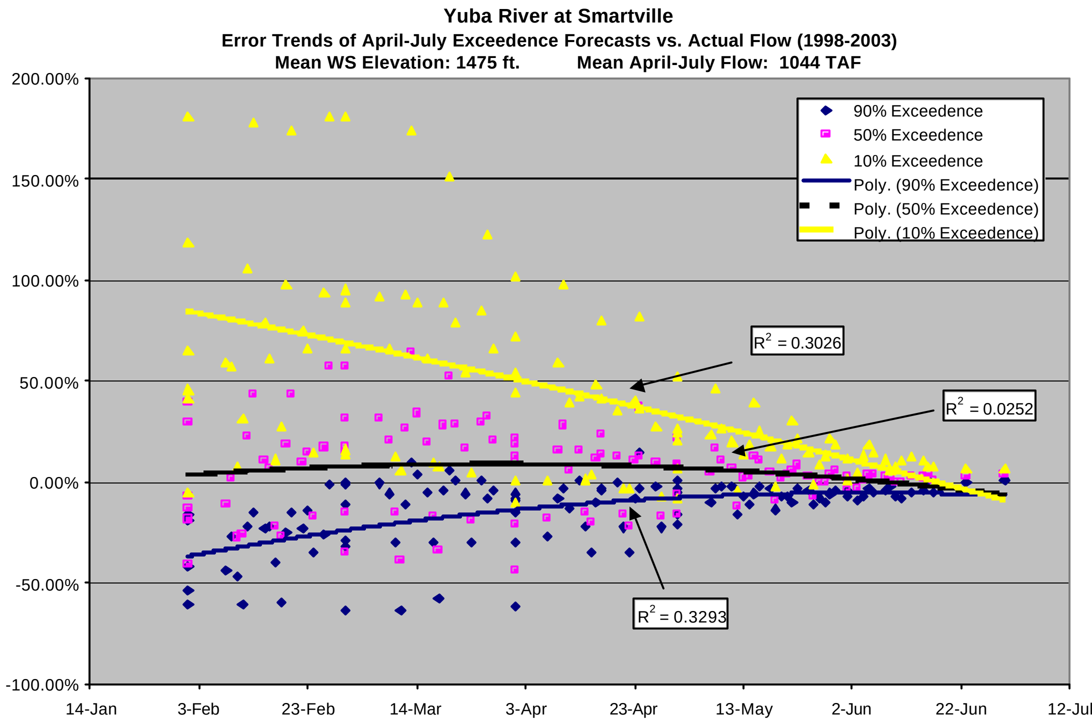

Figure 3B-3. Yuba River Flow Forecast Analysis

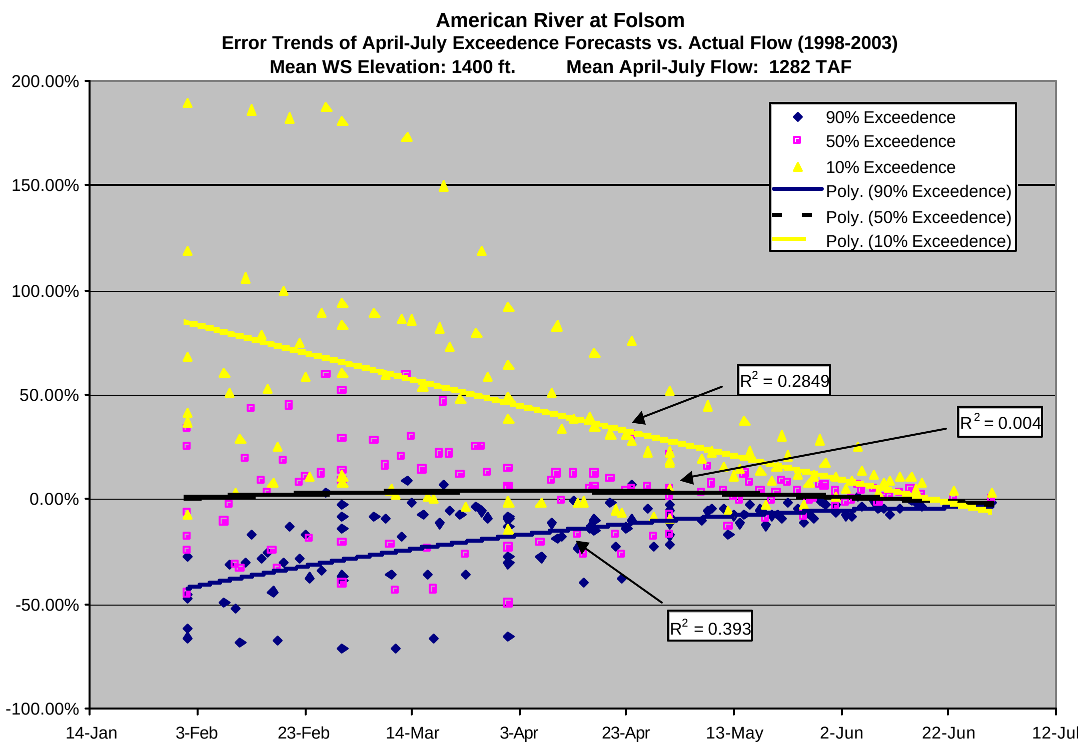

Figure 3B-4. American River Flow Forecast Analysis

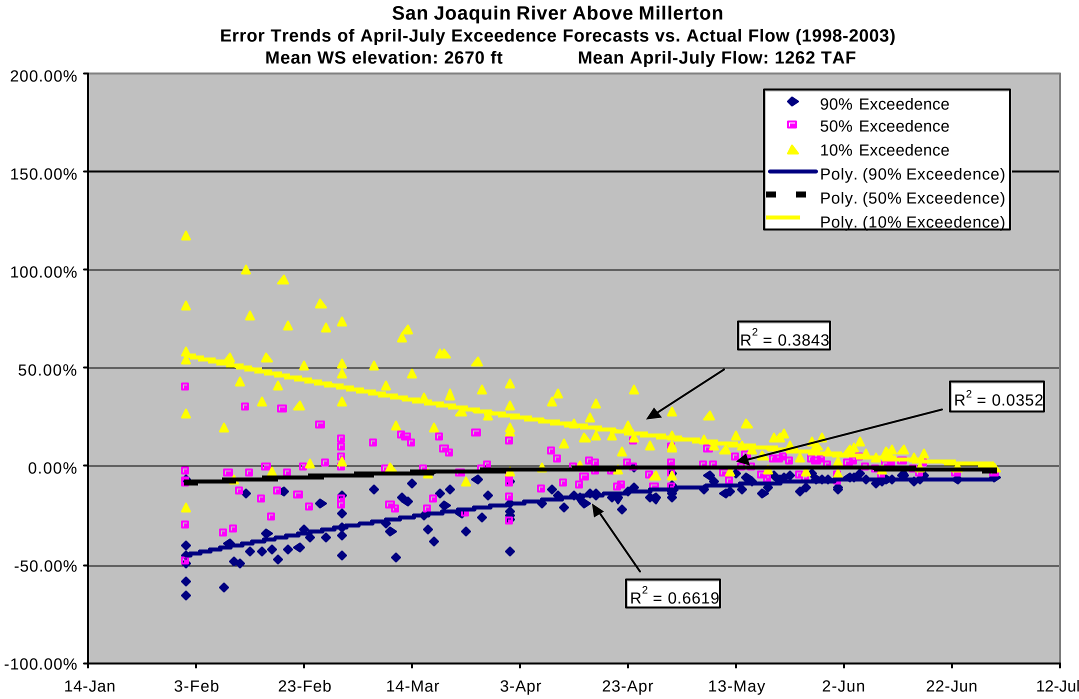

Figure 3B-5. San Joaquin River Flow Forecast Analysis

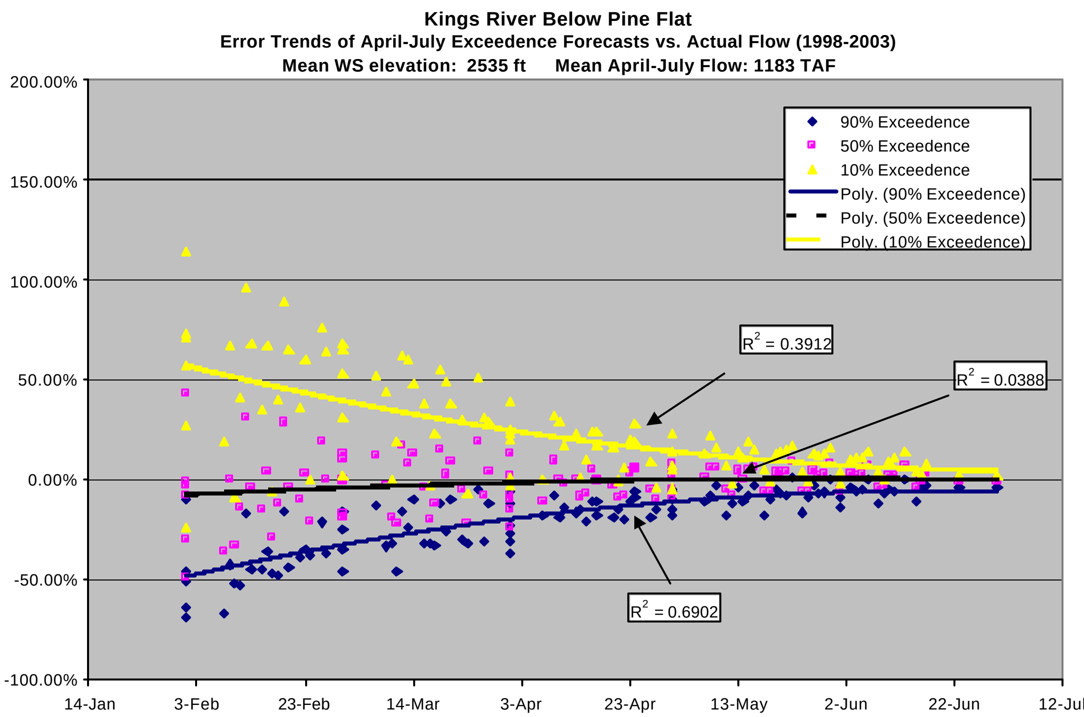

Figure 3B-6. Kings River Flow Forecast Analysis

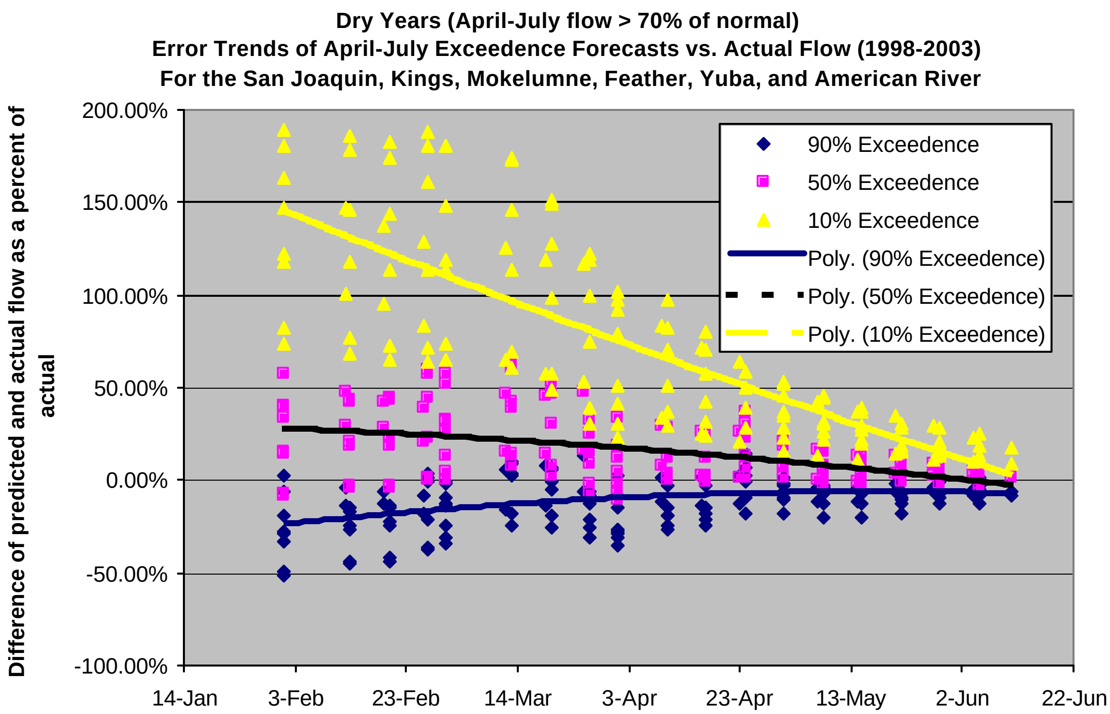

Figure 3B-7. Dry Years Flow Forecast Analysis

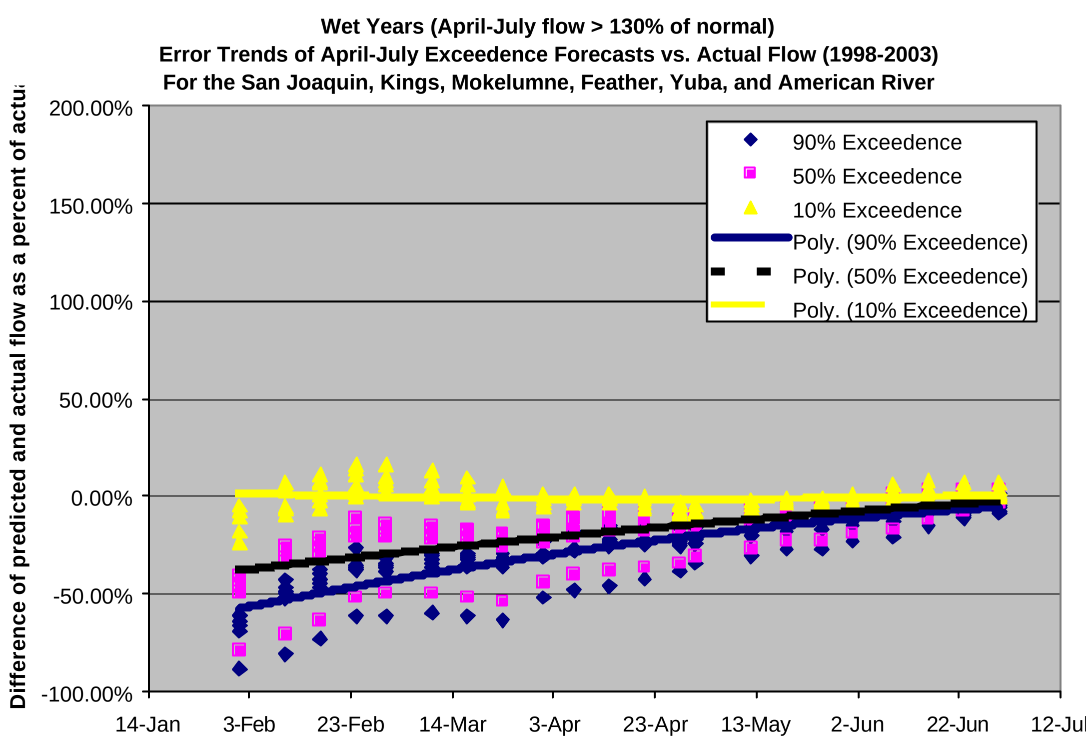

Figure 3B-8. Wet Years Flow Forecast Analysis